Heavy Flavour Jet Substructure

MPP/TUM seminar
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Outline

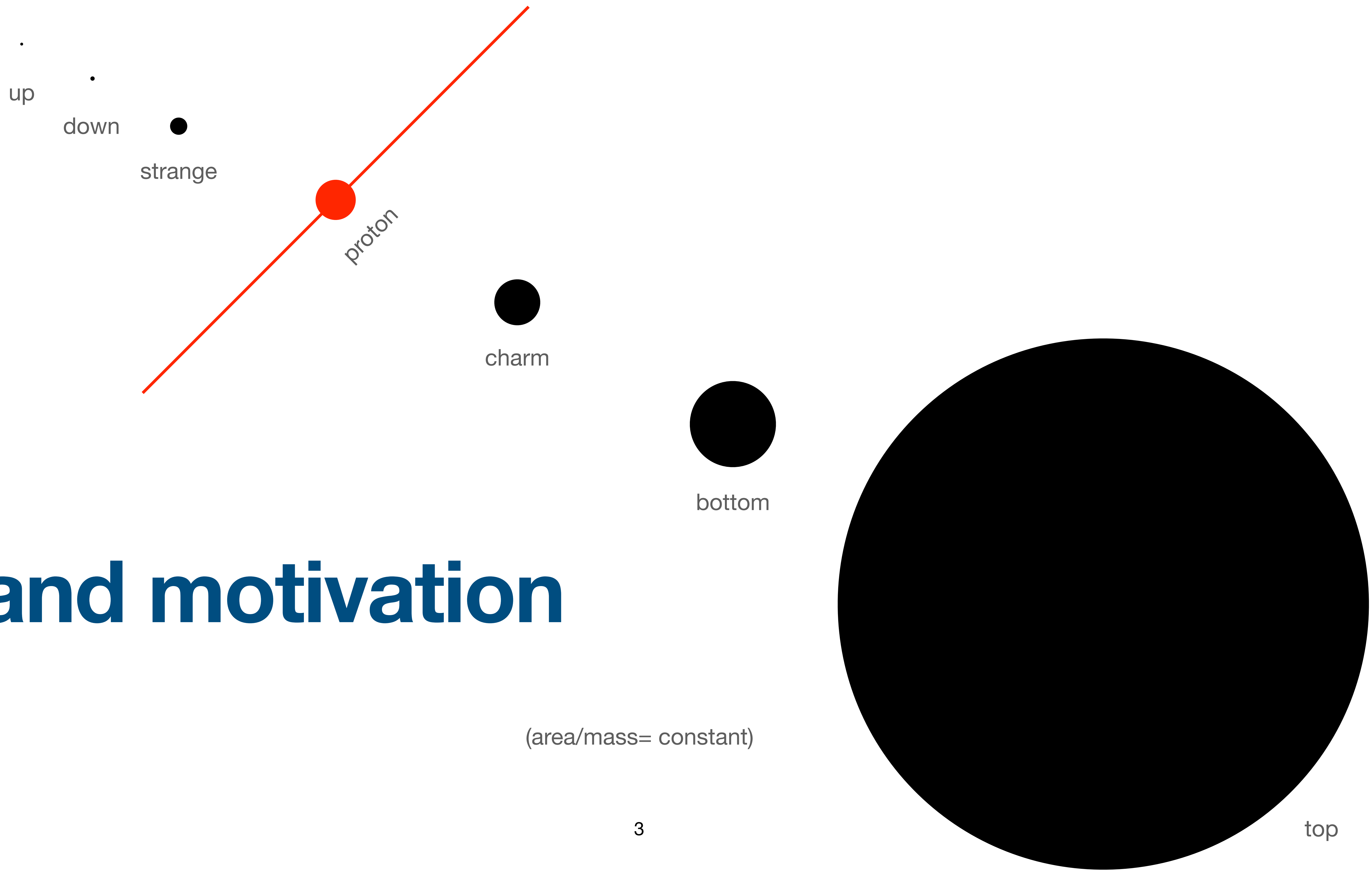
- Introduction and motivation
- Q1: How can we define flavoured jets in a sensible way?

  A1: New flavours of jet flavour
- Q2: How well do we understand QCD final-states with heavy-flavours?

  A2: Heavy-flavour jet substructure

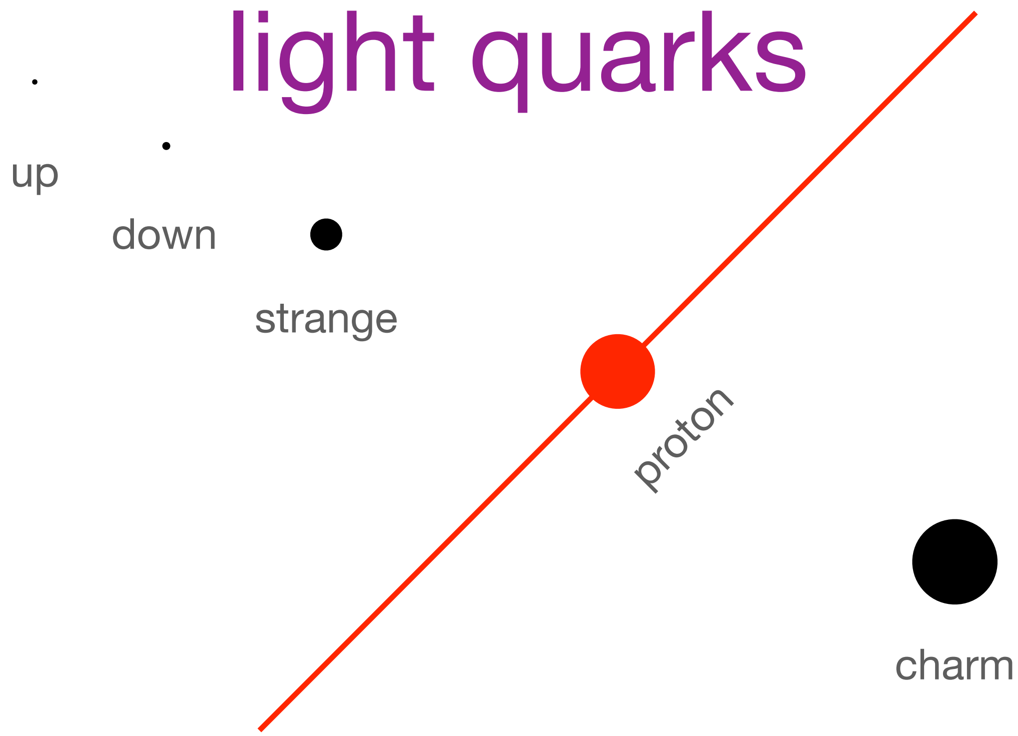
Introduction

and motivation



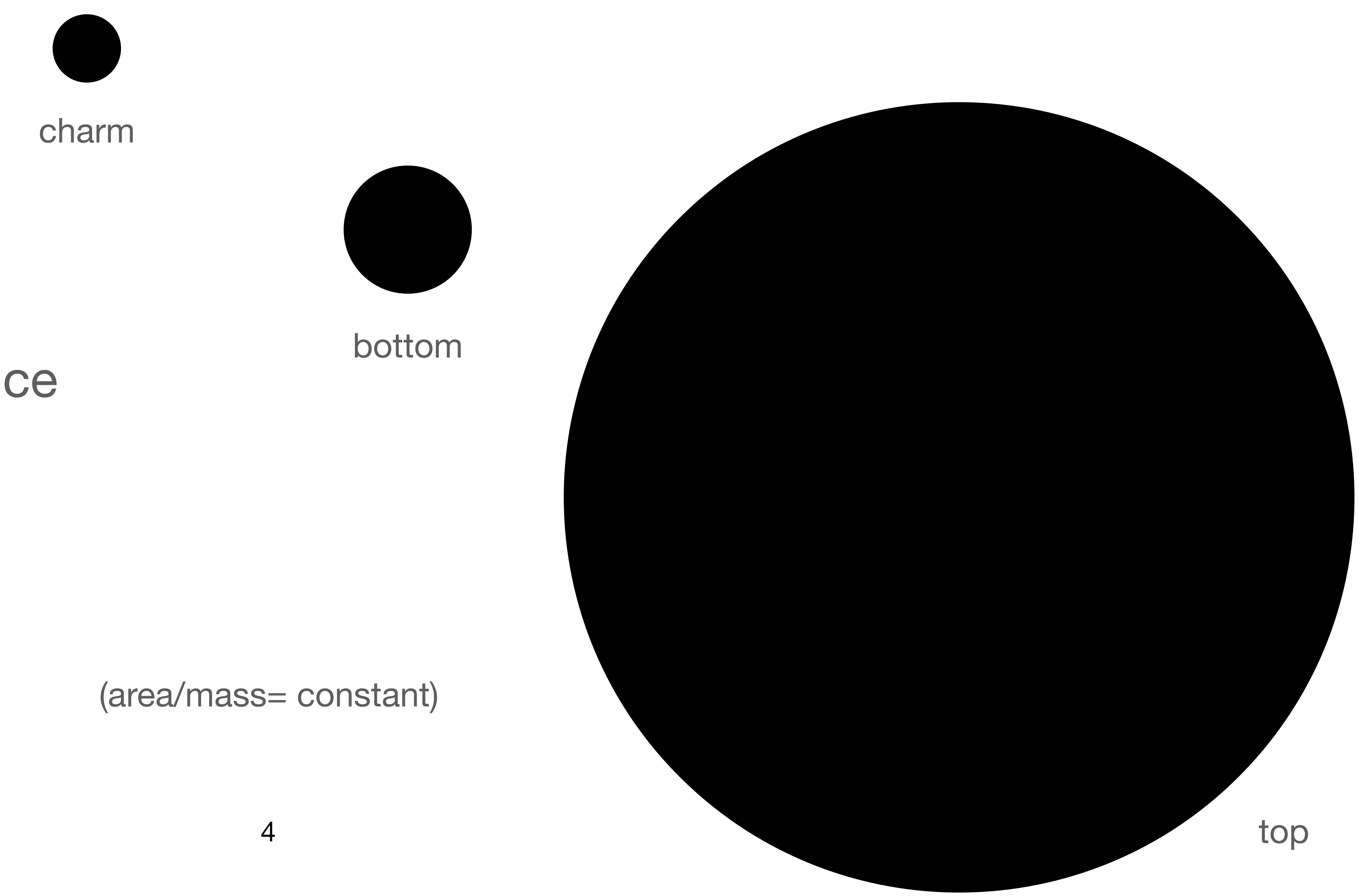
Quark flavours and QCD

light quarks



- strong interactions are flavour-blind: gluons couple to quarks irrespectively of their mass

heavy quarks

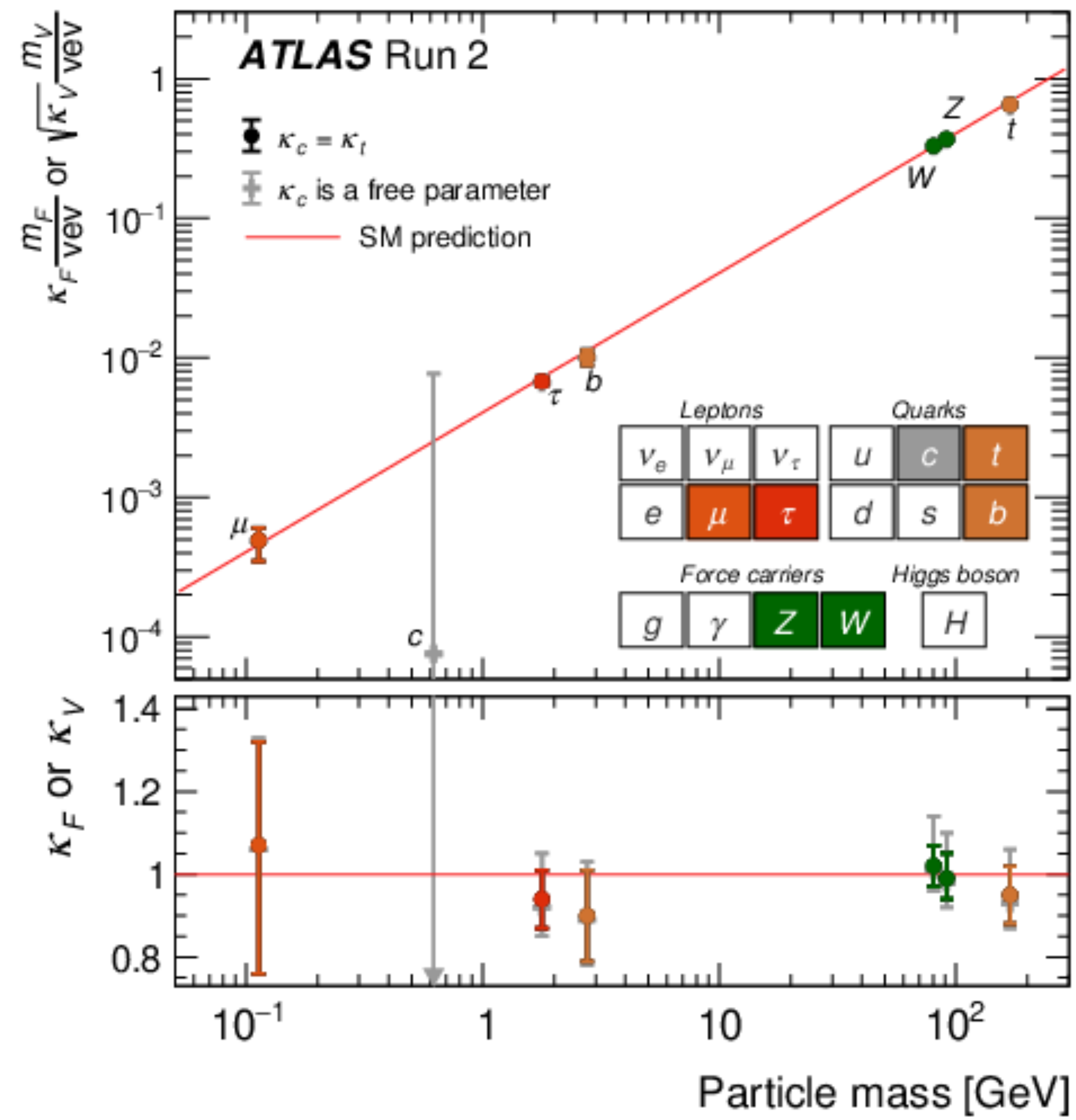


- however, the mass does influence emergent phenomena:
  - hadron-formation
  - jet properties

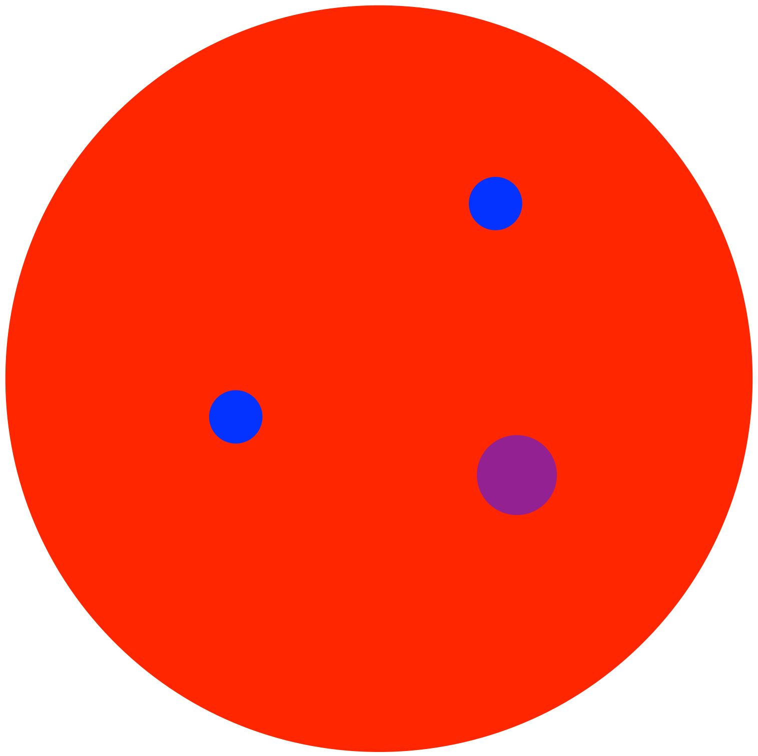
(area/mass= constant)

Heavy quarks to probe the Higgs

- fundamental particles acquire their mass through the Higgs mechanism
- SM prediction: Higgs couplings proportional to the masses
- heavy states have provided us with the first experimental confirmation of the Higgs mechanism



The proton mass

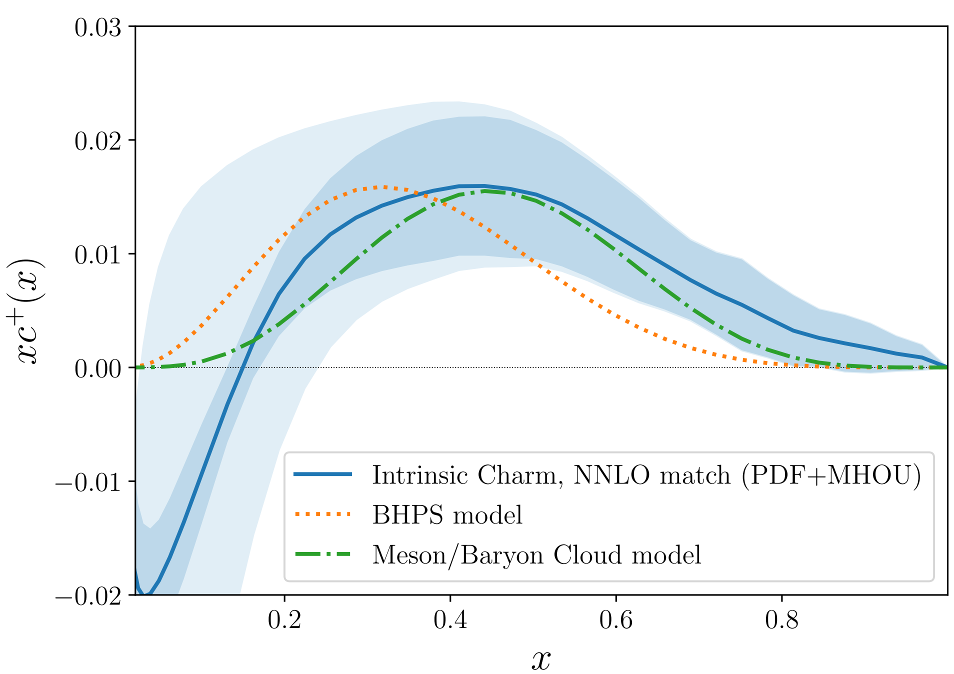


- about 1% of the proton mass comes from m_u and m_d
- the origin of the proton mass is the binding energy of the strong interaction
- hadron mass spectra can be determined from lattice QCD

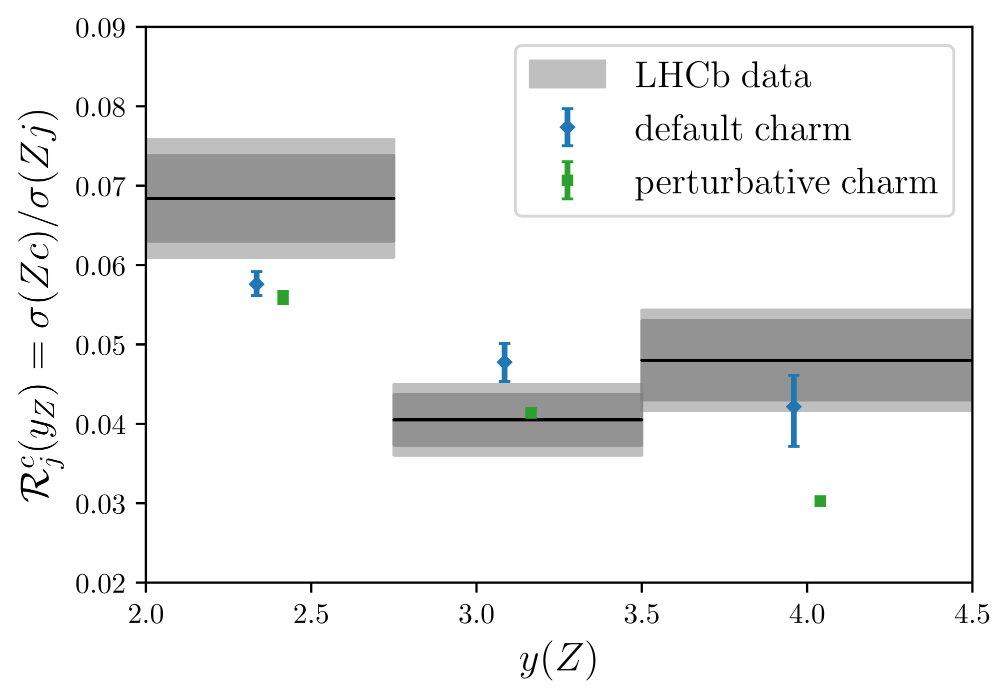
- top quark decays before hadronsing but *b* and *c* fragment into heavy-flavoured hadrons, giving us a different handle to study hadron-formation

There’s charm in the proton!

- collision processes with heavy flavours can also be used to probe any intrinsic component of the proton wave function;
- NNPDF collaboration has shown a 3σ evidence of intrinsic charm in the proton;
- good agreement with theory models and and visible in Z+c data



NNPDF (2022)

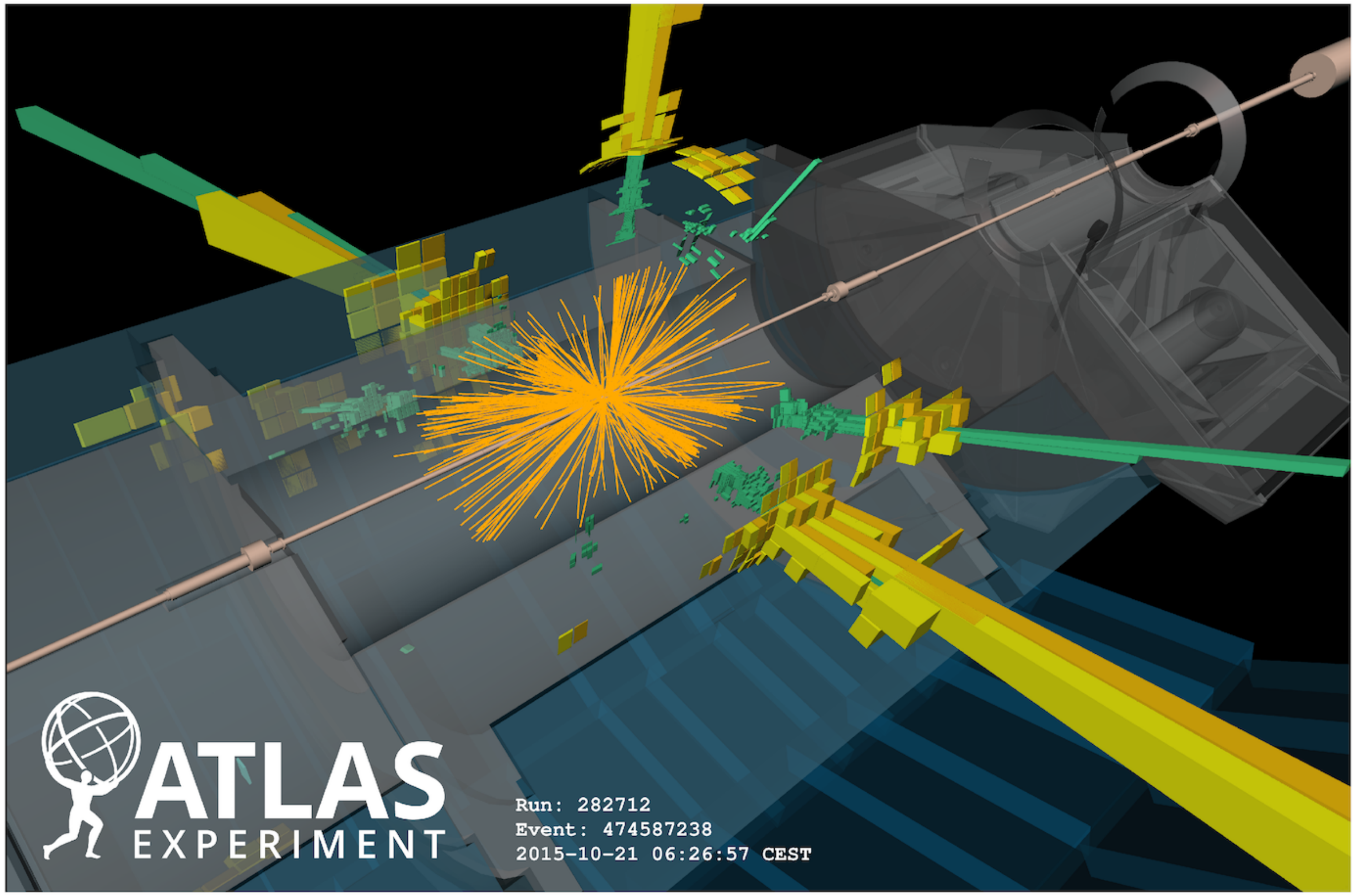


Nature | Vol 608 | 18 August 2022 |

Emergent phenomena: jets

- high-energy collisions ofter results into collimated sprays of particles

- why?



Emergent phenomena: jets

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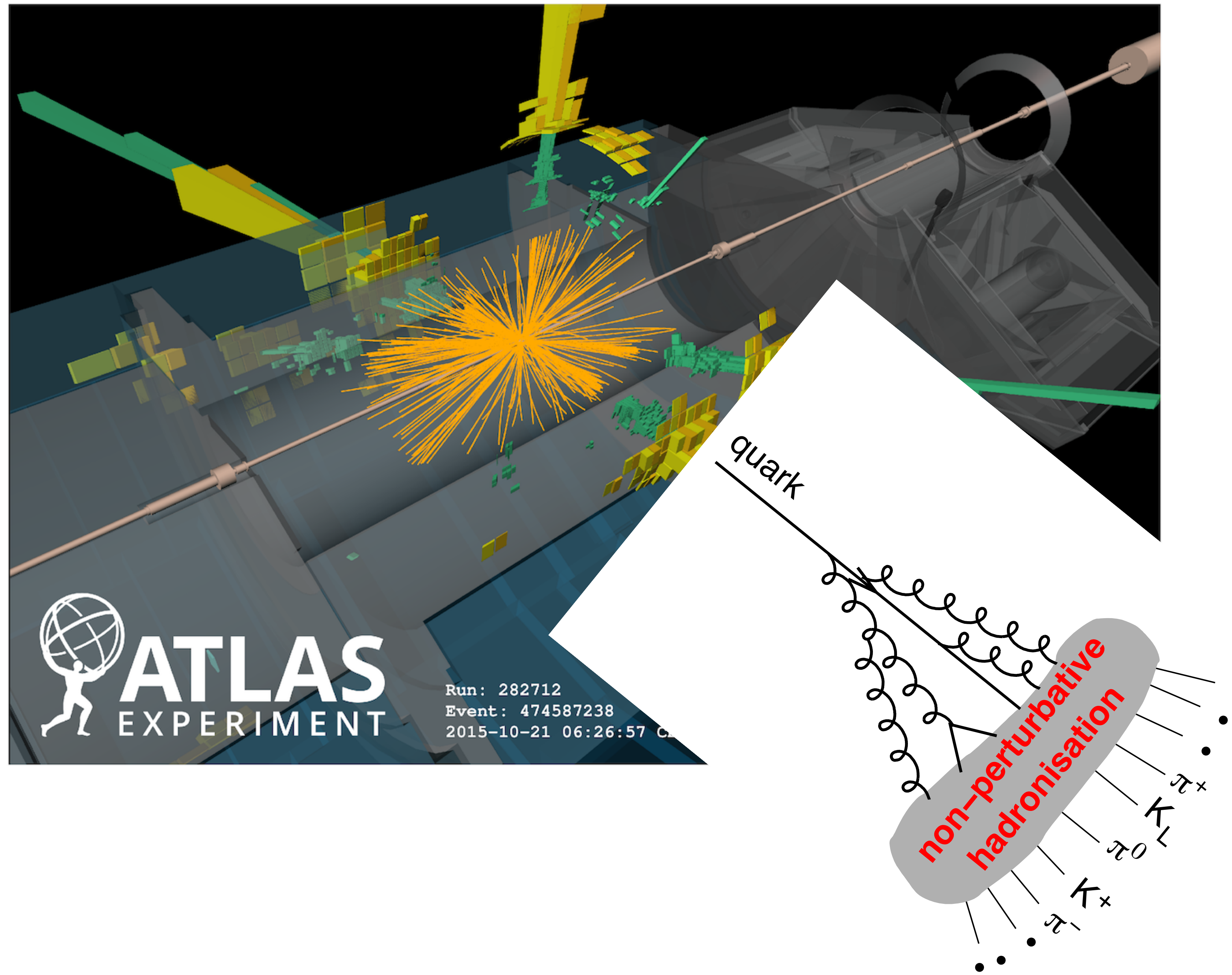
- in a massless theory emissions of collinear partons is enhanced

$$\alpha_s \int \frac{d\theta^2}{\theta^2} \gg 1$$



top

Emergent phenomena: jets

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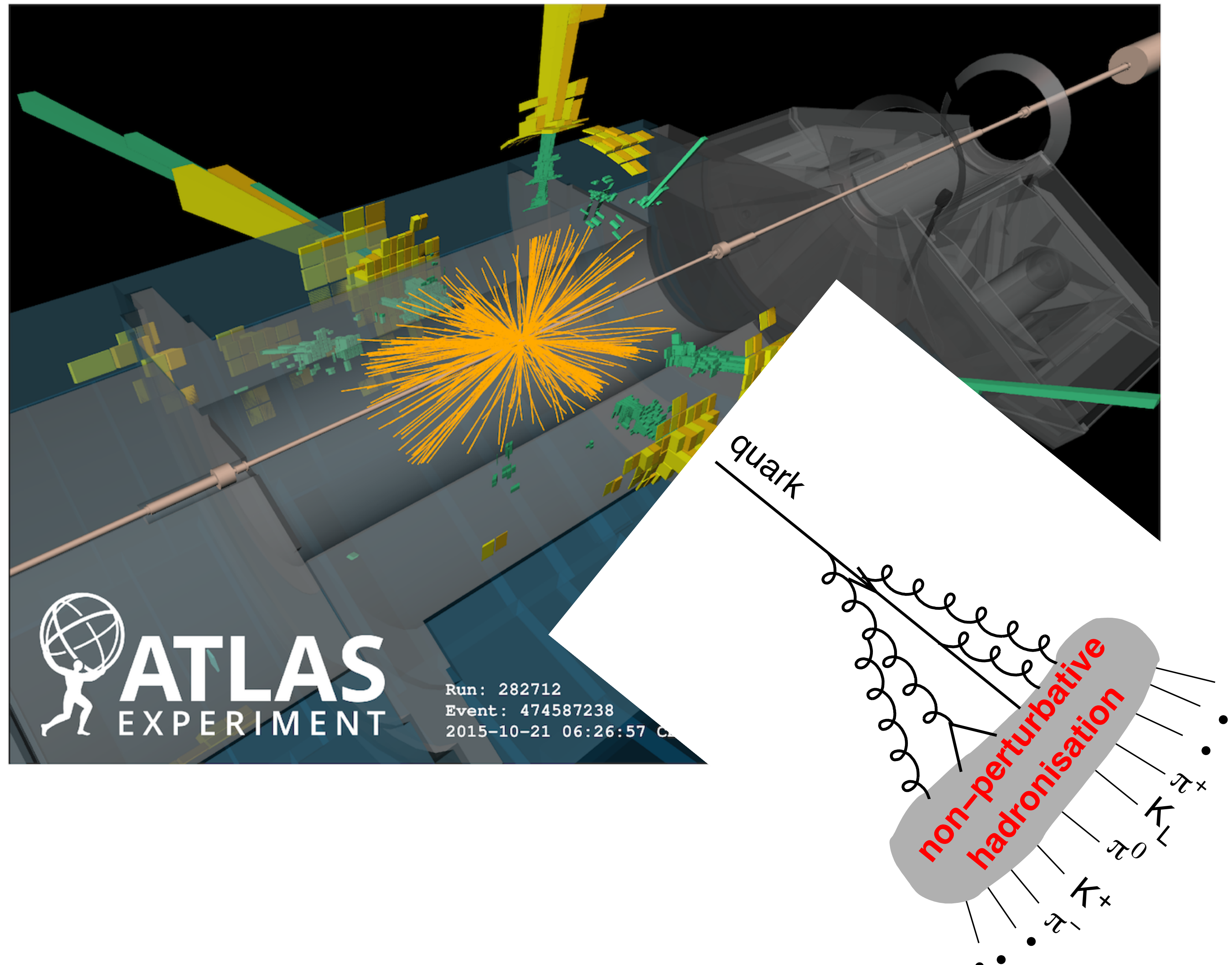

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$$\alpha_s \int \frac{d\theta^2}{\theta^2} \gg 1$$

- quark masses shield collinear singularities

$$\alpha_s \int \frac{d\theta^2}{\theta^2 + \frac{m^2}{E^2}} \sim \int_{\frac{m^2}{E^2}} \frac{d\theta^2}{\theta^2} \sim \alpha_s \log \frac{E^2}{m^2}$$

the so-called "dead cone"

top

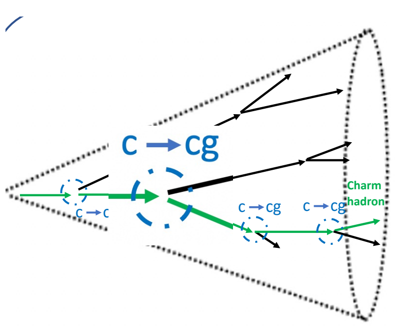
ALICE and the dead cone

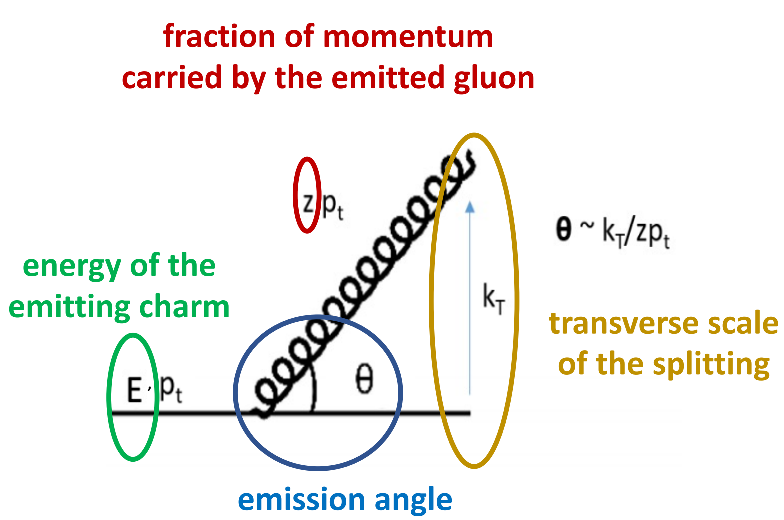
- ALICE recently exploited ideas from modern jet physics (e.g. reclustering) to perform the first direct measurement of the dead cone

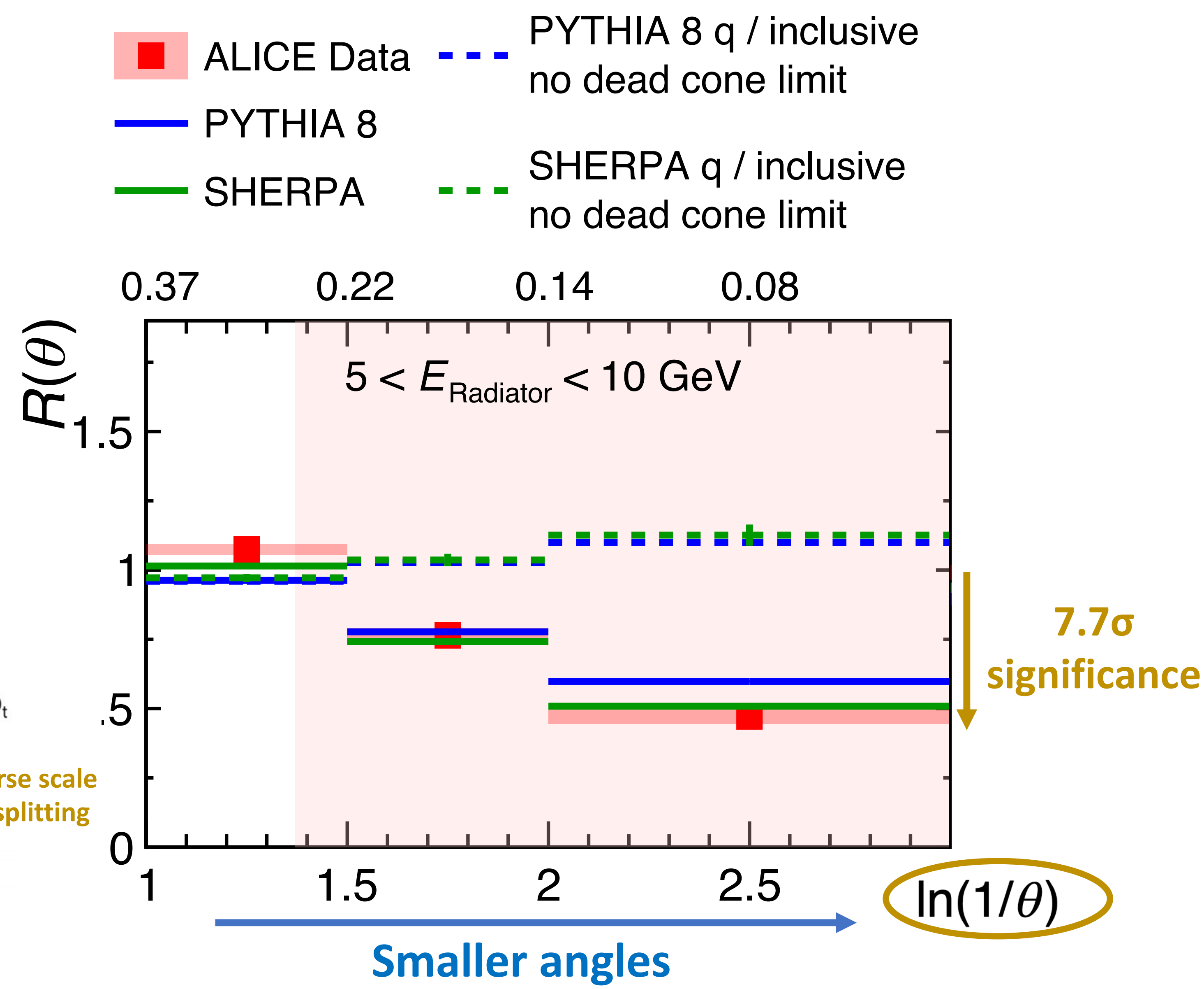
- charm jets are tagged using $D^0 \to K^- \pi^+$

- jets are declustered and the splitting kinematics is recorded

Nature 605 (2022) 440-446



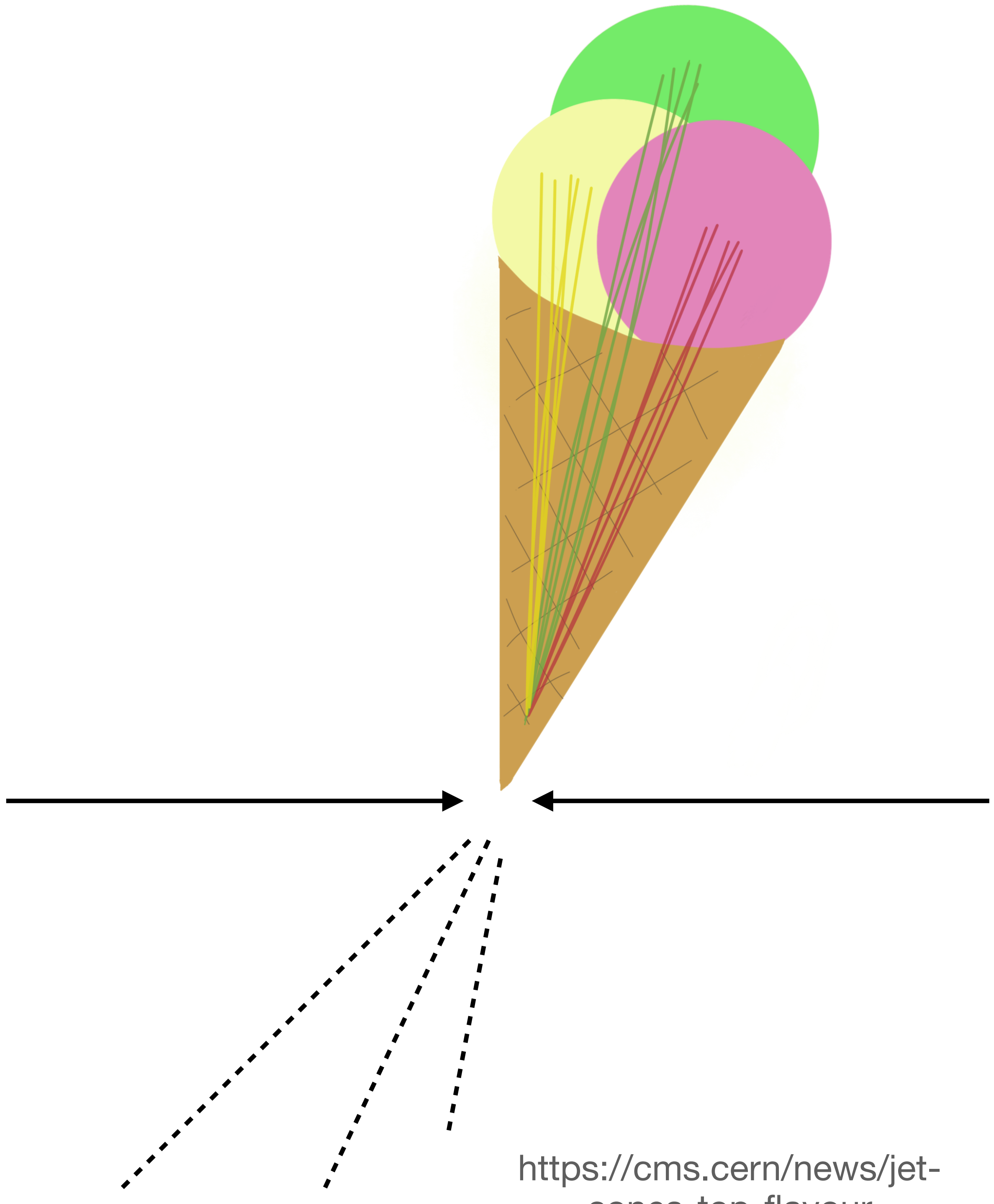




taken from N. Zardoshti's talk at BOOST 2022

Nature | Vol 605 | 19 May 2022 |

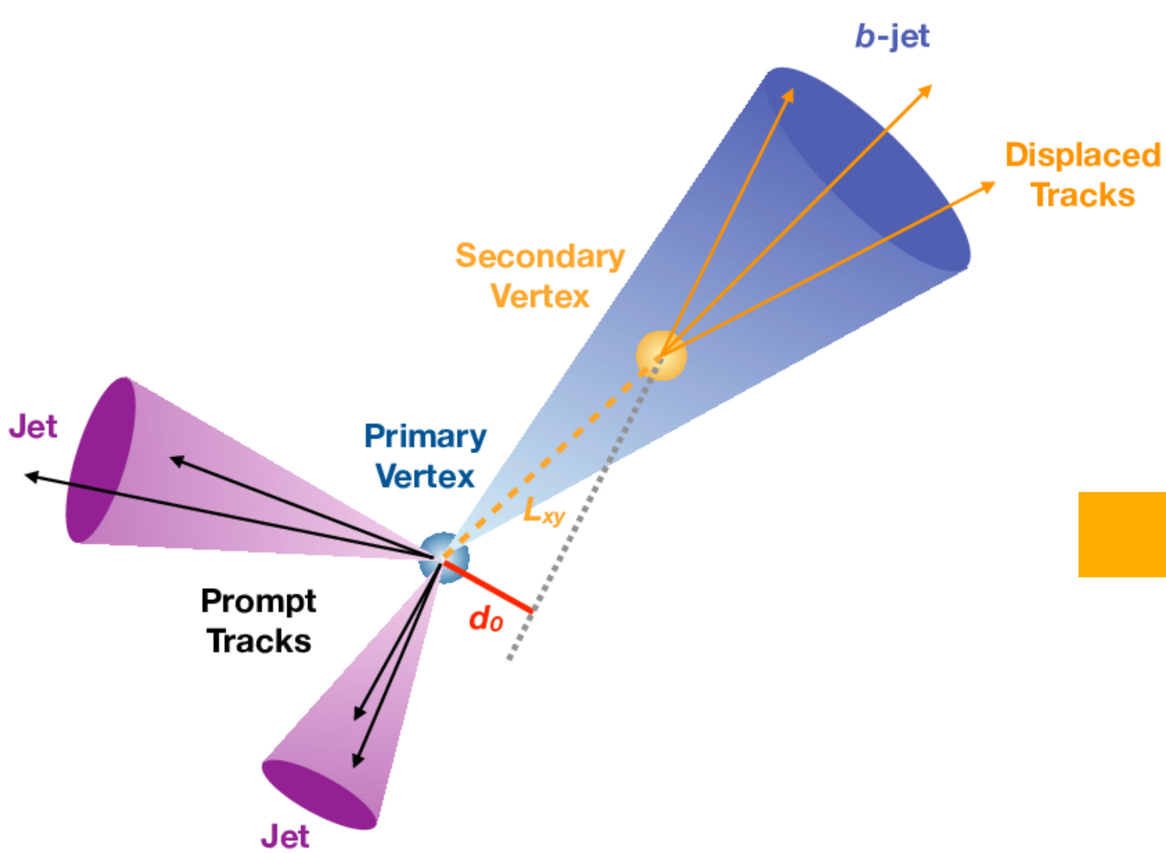
New flavours of jet flavour



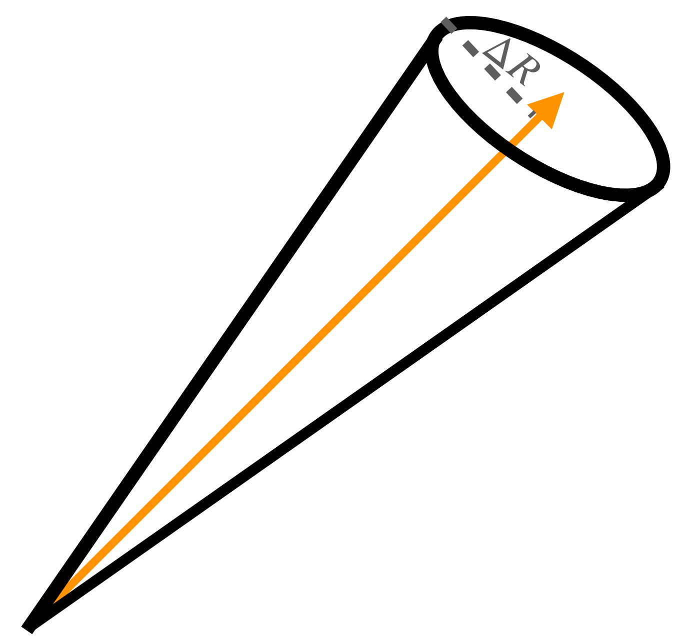
in collaboration with Simone Caletti, Andrew Larkoski, and Daniel Reichelt + Les Houches participants

https://cms.cern/news/jet-cones-top-flavour

Prototype of current definitions



https://cds.cern.ch/record/2771727/plots

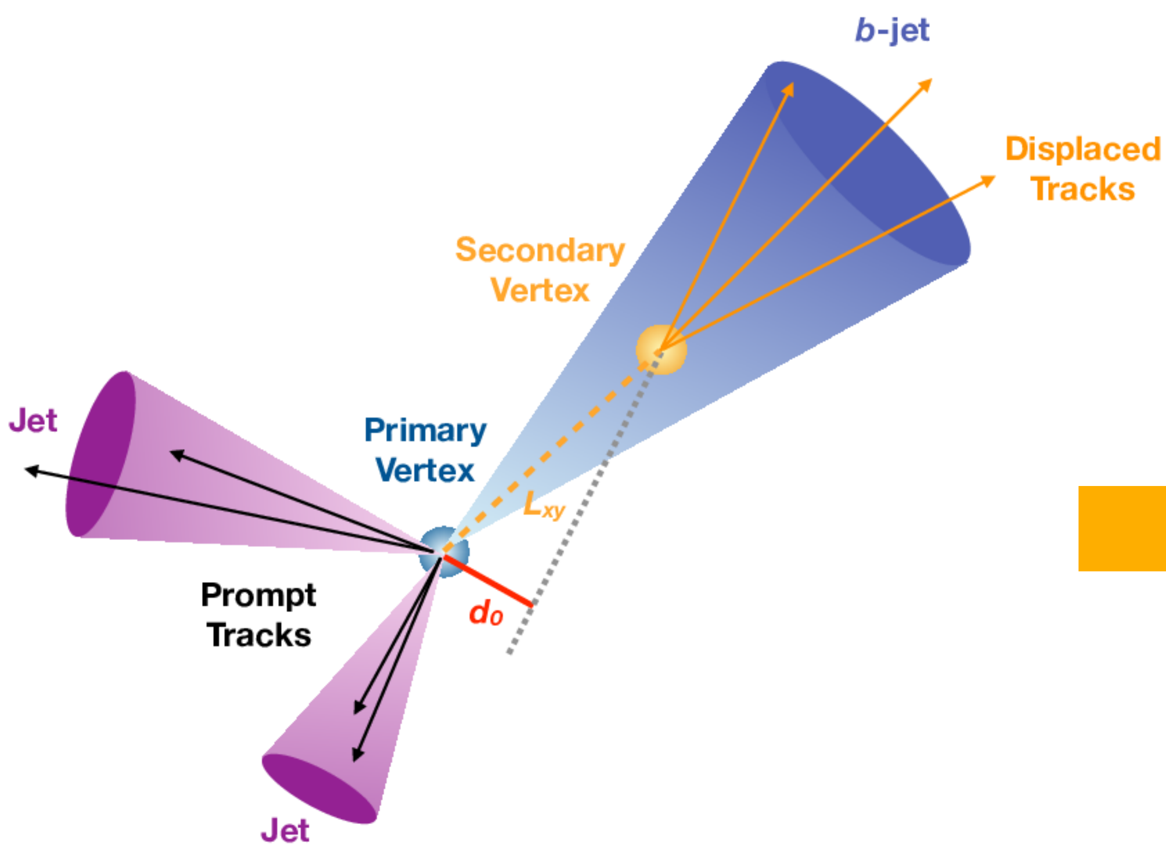


the ΔR labelling

a few things to pay attention to

- take the four-momenta of reconstructed (anti-k_t) jets and B hadrons ($p_T > p_{Tcut} \sim 5$ GeV)
- Assign a B to a jet if $\Delta R < R_0 \sim 0.3$
- If at least one B is assigned to jet J, then J is a b-jet

Prototype of current definitions



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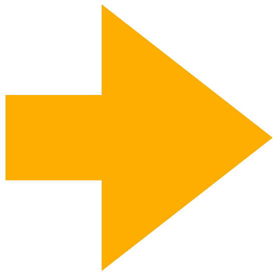

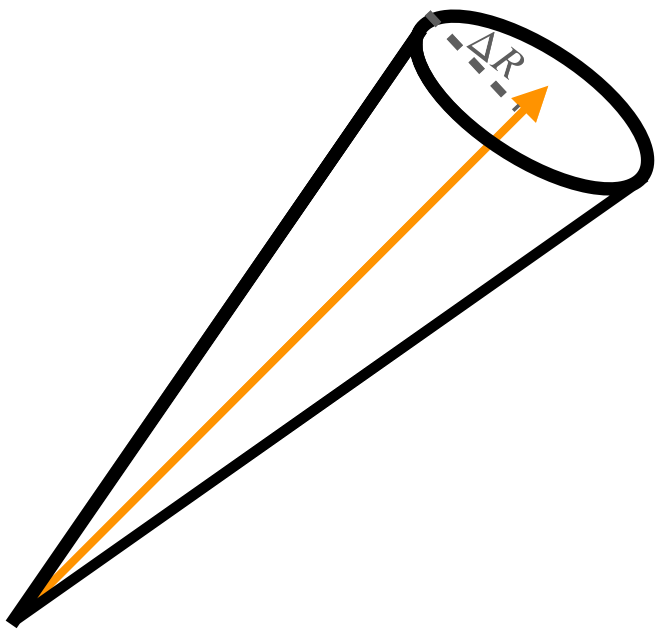

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Thy jet definition shall …

- be simple to implement in an experimental analysis;
- be simple to implement in theoretical calculations;
- be defined at any order of perturbation theory;
- yield finite cross-sections at any order of perturbation theory;
- yield cross-sections and distributions that are relatively insensitive to hadronisation

- jet definitions that respect this Snowmass accord made precision studies of QCD possible:

    Theorists talk about quarks and gluons, experimentalists talk about (truth-level) particles … and things still make sense

- do current definitions of heavy-flavour (HF) jet follow these rules?
- if not, can we do better? Should we?

What can go wrong?

- Infra-Red and Collinear Safety! We need IRC safety if we want to be able to compute things beyond LO

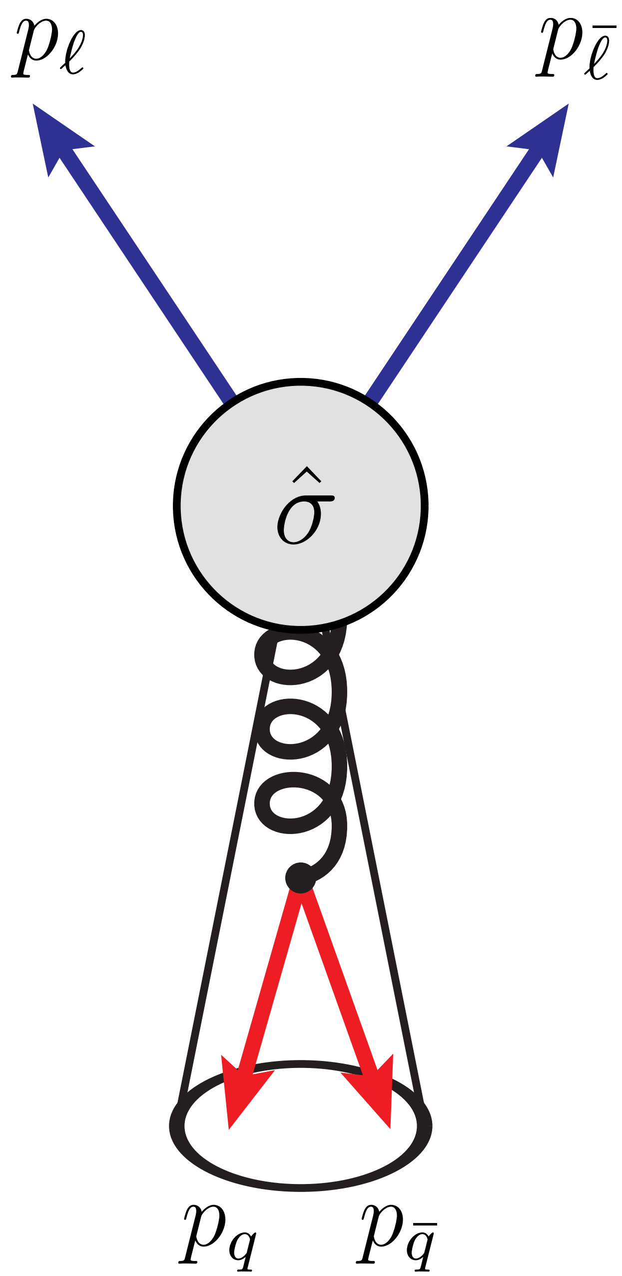
- an observable (or a jet definition) is IRC safe if, in the limit of a collinear splitting, or the emission of an infinitely soft particle, the observable (jet) remains unchanged:

$$O(X; p_1, \ldots, p_n, p_{n+1} \to 0) \to O(X; p_1, \ldots, p_n)$$
$$O(X; p_1, \ldots, p_n \parallel p_{n+1}) \to O(X; p_1, \ldots, p_n + p_{n+1})$$

- an IRC-unsafe HF jet definition with massless partons, leads to divergent results in perturbation theory (you just have to throw them away)

- an IRC-unsafe HF jet definition with massive quarks, leads to finite but IRC-sensitive results in perturbation theory (large logs of m/p_T)

Issue n.1: NLO

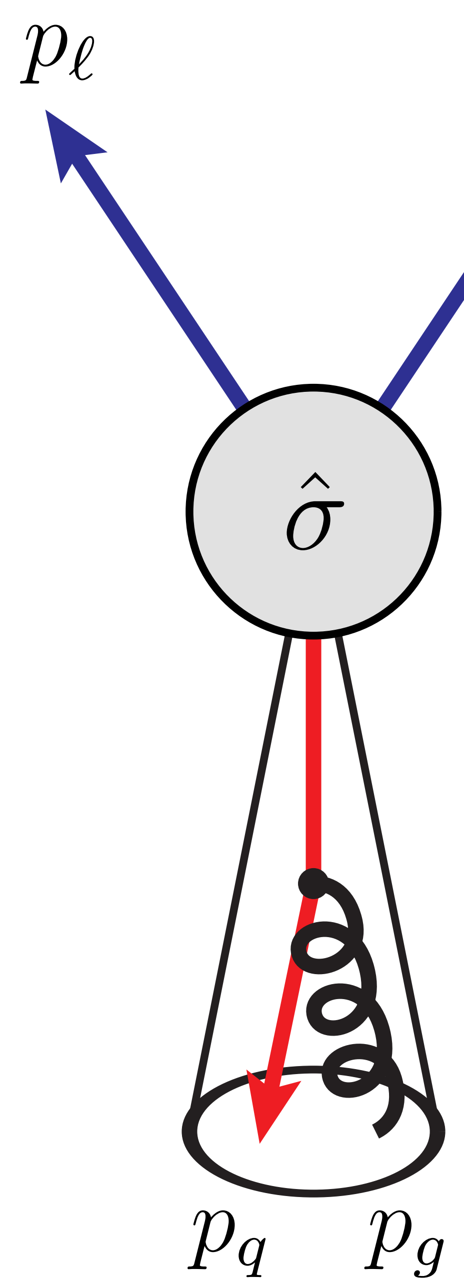


Gauld et. al (2023)

- let's consider Z+b (or c) jet
- problematic configuration at NLO: $g \to b\bar{b}$ is collinear divergent (with zero mass)
- this singularity cancels when we add the corresponding virtual correction, iff real and virtual are in the same flavour bin, i.e. gluon = no net flavour

- this is crucial when looking at distributions that are inclusive over the b-jet substructure (e.g. p_T)
- important effect at high-p_T
- collinear region is avoided if the splitting is resolved (e.g. substructure measurement)

Aside: the p_{Tcut} on hadrons



Gauld et. al (2023)

- in this discussion we focus on parton-level but hadron-level cuts can have significant effects on flavour
- ΔR labelling has a cut on the p_T of the B hadron
- if we implement it at parton level, a soft quark may fail the cut, turning the jet into a gluon one: collinear unsafe!
- proper way to deal with this requires fragmentation functions

Flavour recombination schemes

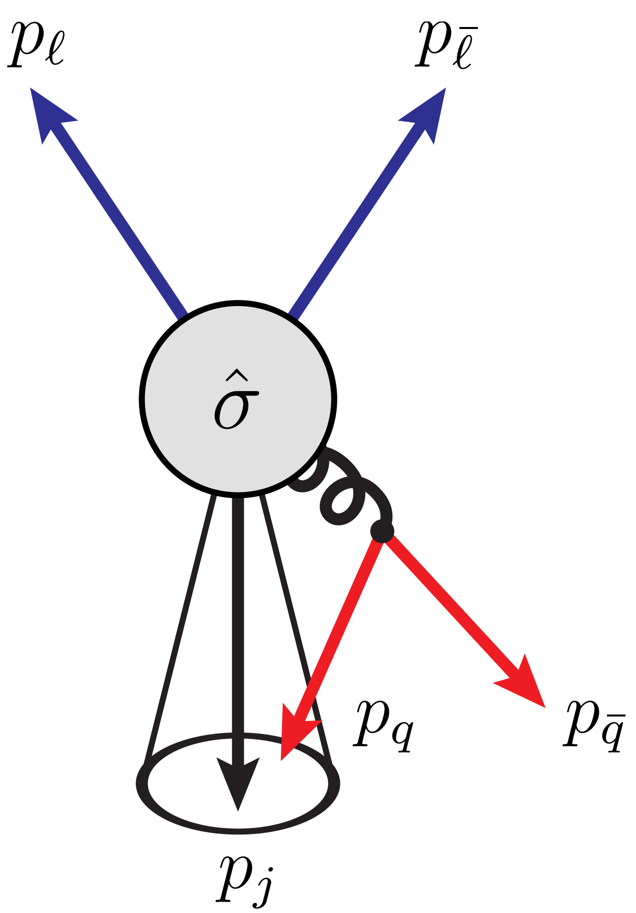
- NLO issues just described are easy to fix in theory-land:

scheme \ jet contents	b	$b+\bar{b}$	$b+b$	
"any flavour"	b	b	b	simplest experimentally (but collinear unsafe for $m_b \to 0$)
net flavour	b	g	$2b$	theoretically "ideal" definition; but not robust wrt B–Bbar oscillations
flavour modulo 2	b	g	g	theoretically OK; robust wrt B–Bbar oscillations

Gavin Salam's talk at Durham workshop

- this comes with large experimental baggage (reconstruction, mistag,…)
- Can we do better? Should we?

Issue n.2: NNLO



Gauld et. al (2023)

- theoretically, things become rather intricate at NNLO
- a soft $g \to b\bar{b}$ splitting can alter the flavour of the jet
- this leads to an IR divergence (sensitivity) for massless (massive) quarks
- counting net flavour is not enough for solve this one and we have to reconsider the jet algorithm

The old solution: flavour-k_t

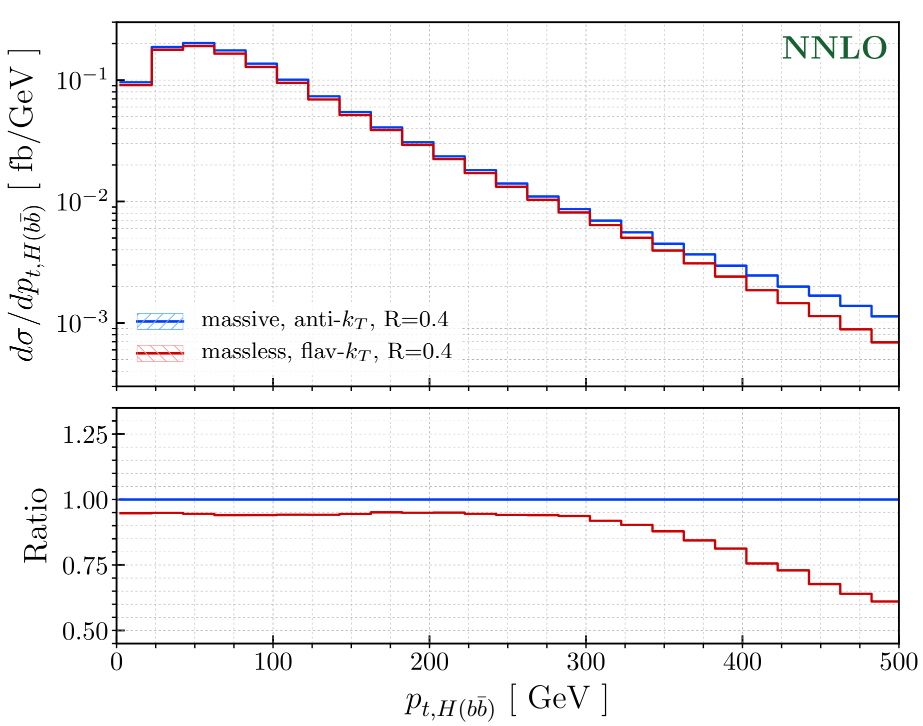
- introduce flavour-sensitive metric reflects the absence of soft quark singularities:

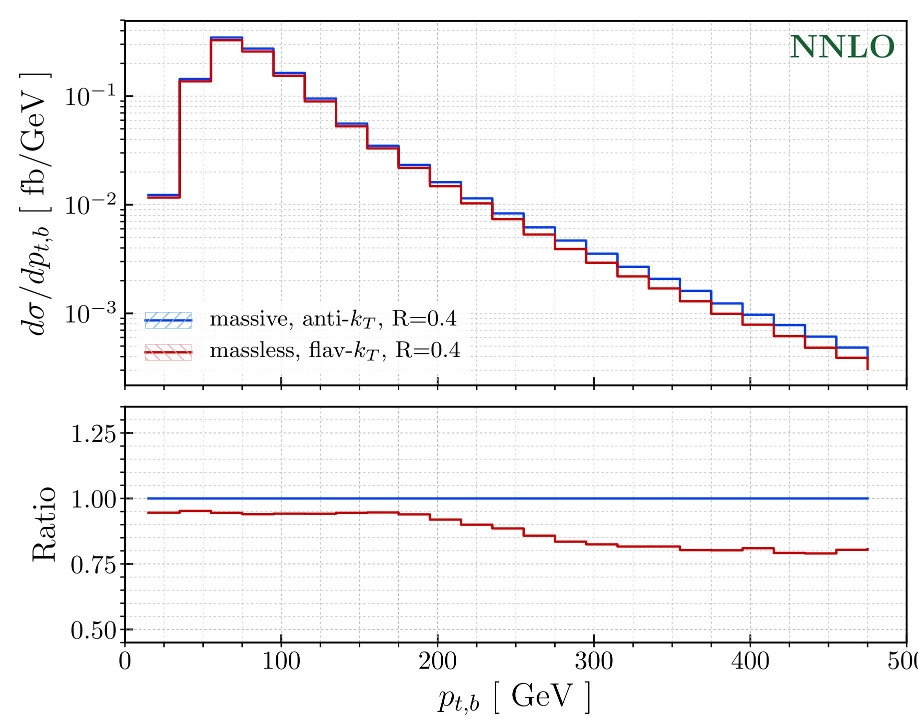
$$d_{ij}^{(F)} = (\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2) \times \begin{cases} \max(k_{ti}^2, k_{tj}^2)\,, & \text{softer of } i, j \text{ is flavoured,} \\ \min(k_{ti}^2, k_{tj}^2)\,, & \text{softer of } i, j \text{ is flavourless,} \end{cases}$$

Banfi Salam Zanderighi (2006)

- flavour-k_t is IRC safe because it tends to recombine together the problematic soft pair;

- however, the use this algorithm in experimental analysis is far from straightforward:
  - obviously, it's not anti-k_t, so resulting jets have different kinematics
  - it requires knowledge of the flavour at each step of the clustering

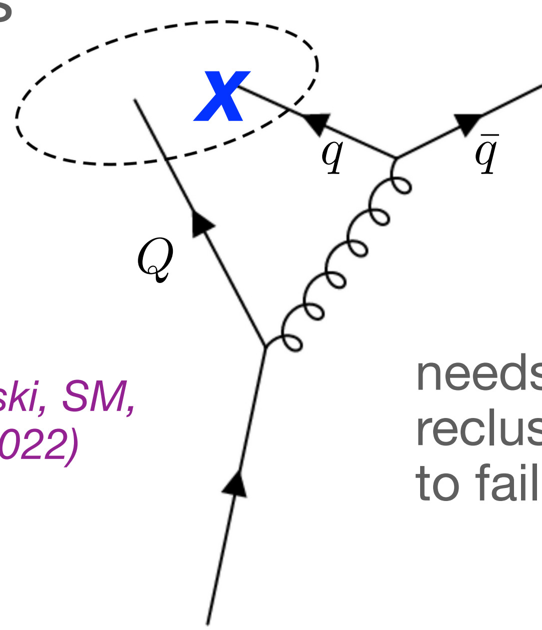




Behring et. al (2020)

Four(!) new ideas

1. use Soft Drop to remove soft quarks

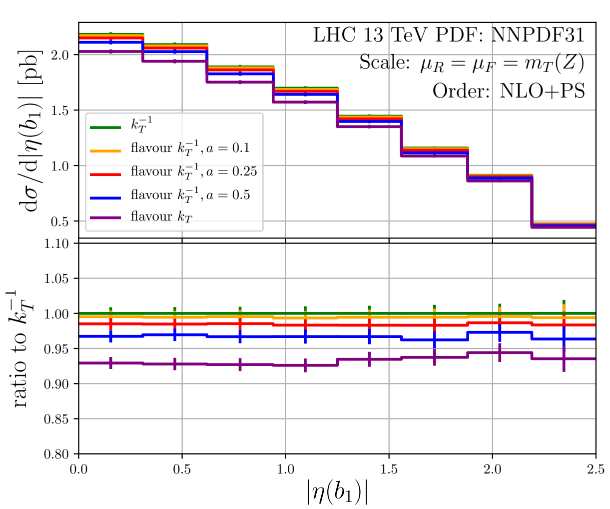


Caletti, Larkoski, SM, Reichelt (2022)

needs JADE as a recluster, known to fail at 3 loops

2. define a flavour algorithm that resembles anti-k_t

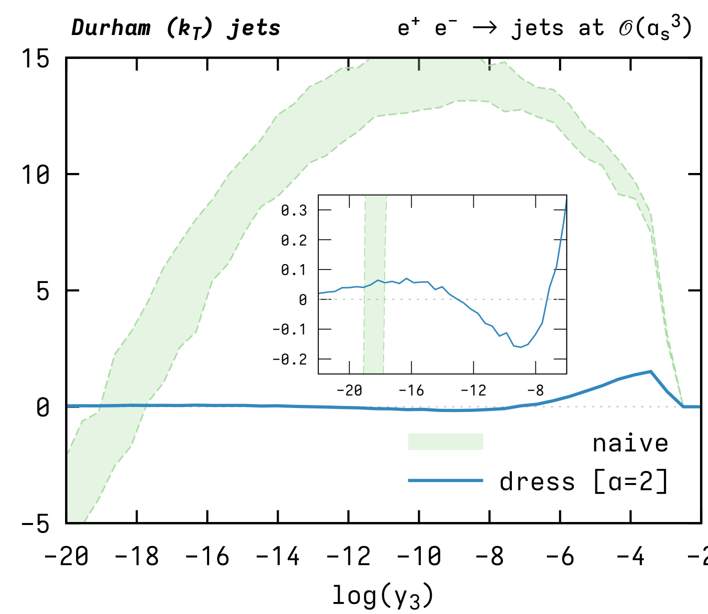
$$d_{ij}^{(F)} \equiv d_{ij} \times \begin{cases} \mathcal{S}_{ij}, & \text{if both } i \text{ and } j \text{ have non-zero flavour of opposite sign,} \\ 1, & \text{otherwise.} \end{cases}$$



still needs some (small) unfolding

Czakon, Mitov, Poncelet (2022)

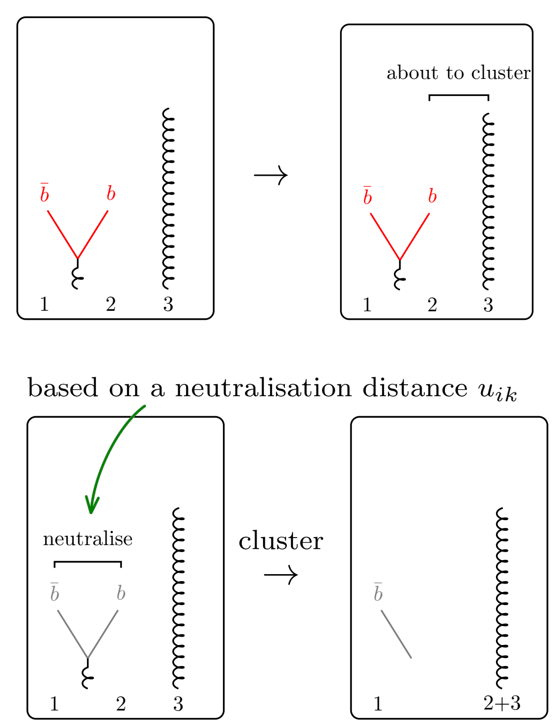
3. construct a flavour dressing for a given jet



accumulates the flavour information in order to assign the flavour of a jet

Gauld, Huss, Stagnitto (2022)

4. interleaved flavour neutralisation

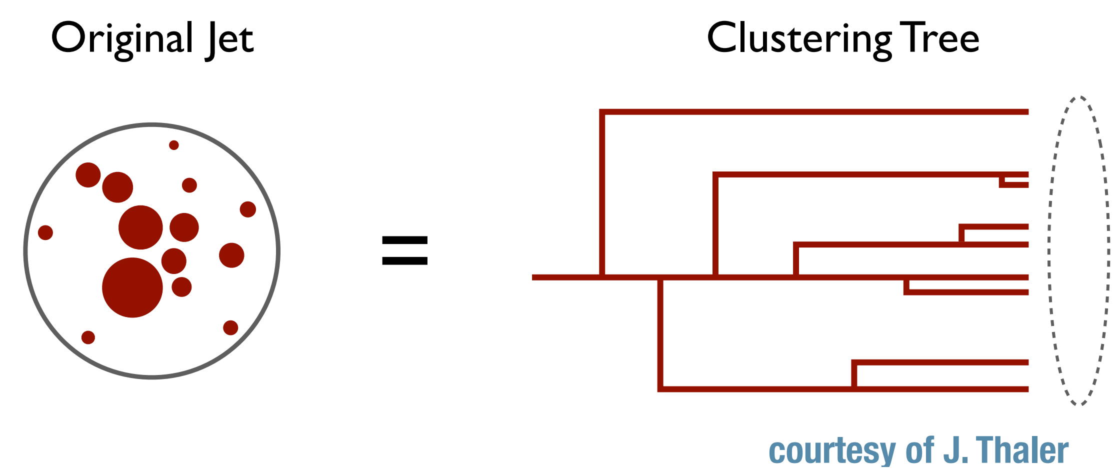


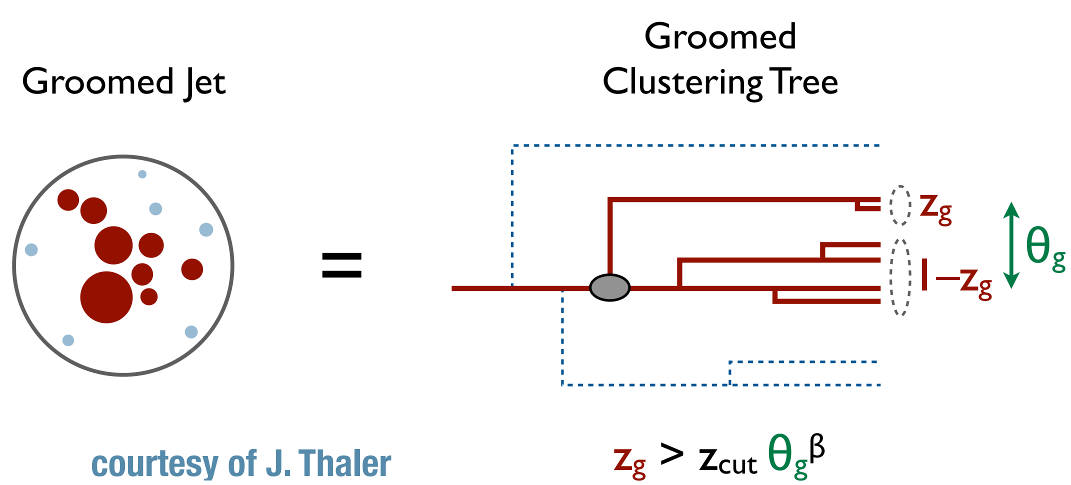
neutralise = remove the (opposite) flavour of both 1 & 2 while maintaining kinematics

Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler (2023)

Aside: Soft Drop (mMDT)

- efficient and robust *grooming* and *tagging* have been developed and exploited at the LHC
- Soft Drop aims to clean up a jet by removing soft radiation





- compute momentum sharing and if it fails the soft drop condition, remove the branch

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} \qquad z_g < z_{\text{cut}}\theta_g^{\beta}$$

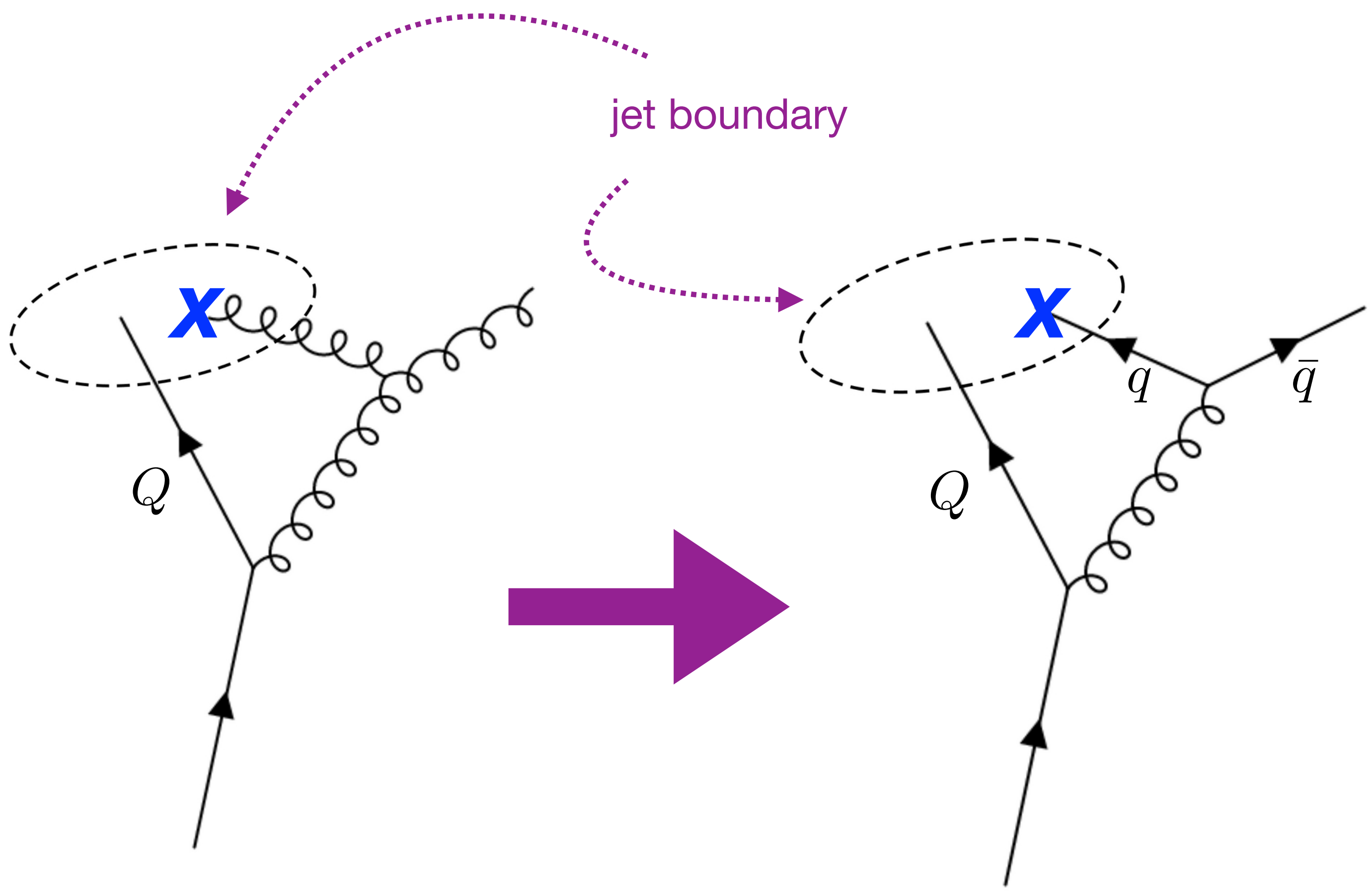
Dasgupta, Fregoso, SM, Salam (2013)

Larkoski, SM, Soyez, Thaler (2014)

What about Soft Drop jets?

- grooming algorithms remove soft radiation from jets
- in particular is Soft Drop is beneficial in the context of non-global logarithms
- the problematic configurations are similar

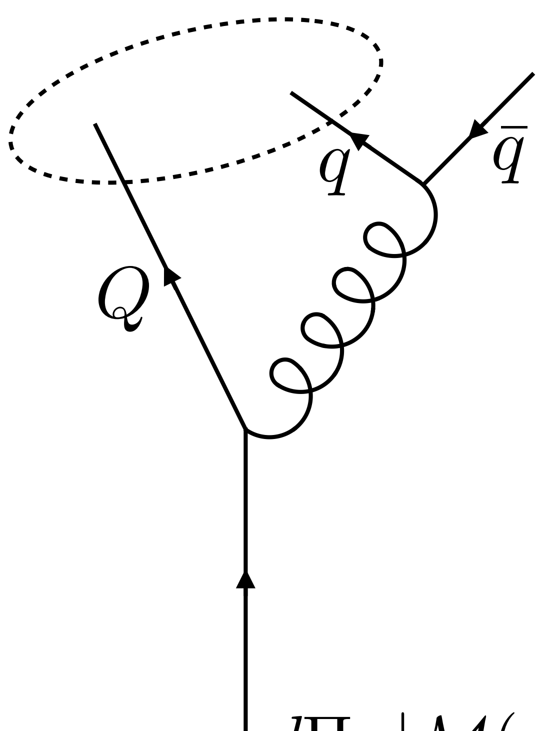
Larkoski, Marzani, Soyez, Thaler (2014)



- so the idea is:
  - cluster jets with any algorithm you wish
  - apply Soft Drop and measure the flavour
- this is experimentally viable, it is IRC safe?

Soft Drop flavour at NNLO

- if the dashed oval represents the jet boundary (NGLs configuration), Soft Drop screens the singularity
- if the dashed oval represents the effective grooming boundary (clustering log configuration), Soft Drop fails to screen the singularity



Why is that?

$$\Theta_{\rm SD}^{\rm C/A} = \Theta(\theta^2_{Q\bar{q}} - \theta^2_{Qq})\Theta(\theta^2_{q\bar{q}} - \theta^2_{Qq})\Theta\left(z_q - z_{\rm cut}\left(\frac{\theta^2_{Qq}}{R^2}\right)^{\beta}\right)\Theta\left(z_{\rm cut}\left(\frac{\theta^2_{Q\bar{q}}}{R^2}\right)^{\beta} - z_{\bar{q}}\right)$$

C/A clustering

quark passes Soft Drop

antiquark fails Soft Drop

$$d\Pi_3\,|\mathcal{M}(z_q, z_{\bar{q}})|^2\,\Theta_{\rm SD}$$

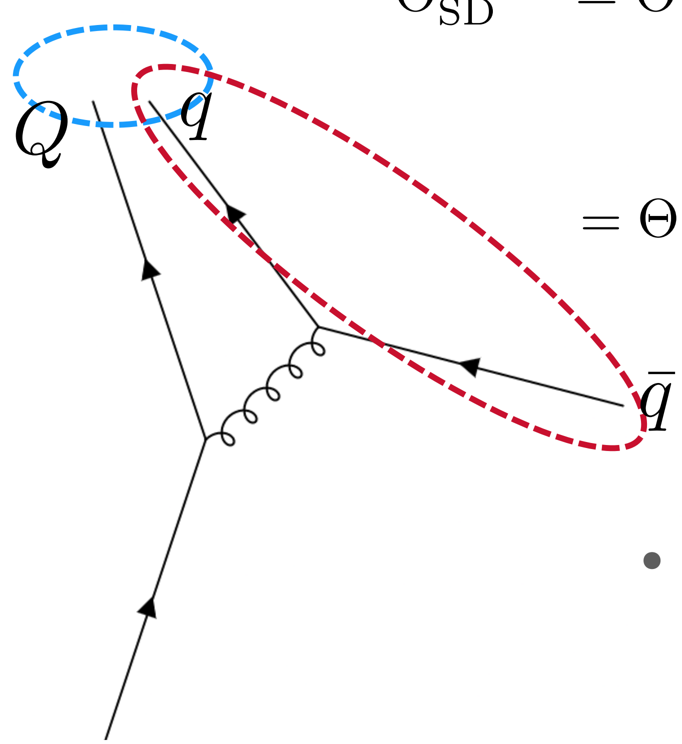
$$\simeq d\Pi_3\,|\mathcal{M}(x_q, x_{\bar{q}})|^2\,\Theta(\theta^2_{Q\bar{q}} - \theta^2_{Qq})\Theta(\theta^2_{q\bar{q}} - \theta^2_{Qq})\Theta\left(x_q - 1\right)\Theta\left(1 - x_{\bar{q}}\right)$$

rescaling: $z_q = x_q z_{\rm cut}\left(\frac{\theta^2_{Qq}}{R^2}\right)^{\beta}$

which is singular in the collinear limit

Jade Soft Drop

- Can we modify Soft Drop to save the day?
- we can change the algorithm used for reclustering
- gen-k_t algorithms do not cluster two soft particles together, if there is a hard particle around at smaller angle, but Jade does
- let's look at the problematic configuration with Jade reclustering



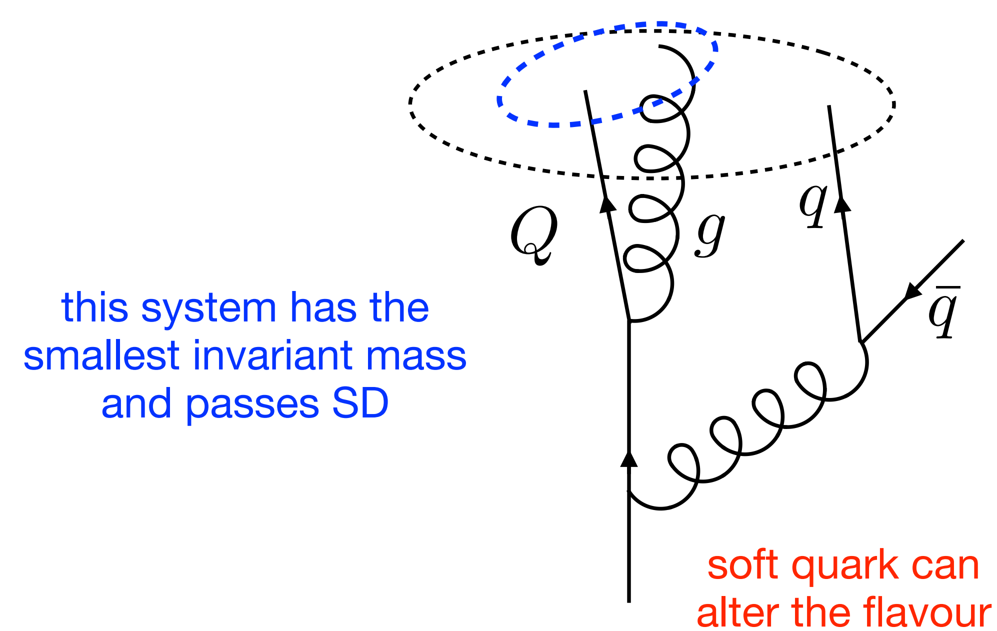
$$\Theta_{\rm SD}^{\rm JADE} = \Theta(m_{Q\bar{q}}^2 - m_{Qq}^2)\Theta(m_{q\bar{q}}^2 - m_{Qq}^2)\ \Theta\left(z_q - z_{\rm cut}\left(\frac{\theta_{Qq}^2}{R^2}\right)^\beta\right)\Theta\left(z_{\rm cut}\left(\frac{\theta_{Q\bar{q}}^2}{R^2}\right)^\beta - z_{\bar{q}}\right)$$

$$= \Theta\left(x_{\bar{q}}\theta_{Q\bar{q}}^{2(\beta+1)} - x_q\theta_{Qq}^{2(\beta+1)}\right)\Theta\left(x_{\bar{q}}z_{\rm cut}\left(\frac{\theta_{Q\bar{q}}^2}{R^2}\right)^\beta \theta_{q\bar{q}}^2 - \theta_{Qq}^2\right)\Theta\left(x_q - 1\right)\Theta\left(1 - x_{\bar{q}}\right)$$

- with Jade reclustering energies and angles are coupled even after rescaling: the singularity is successfully screened

Problems at N^{3}LO and beyond

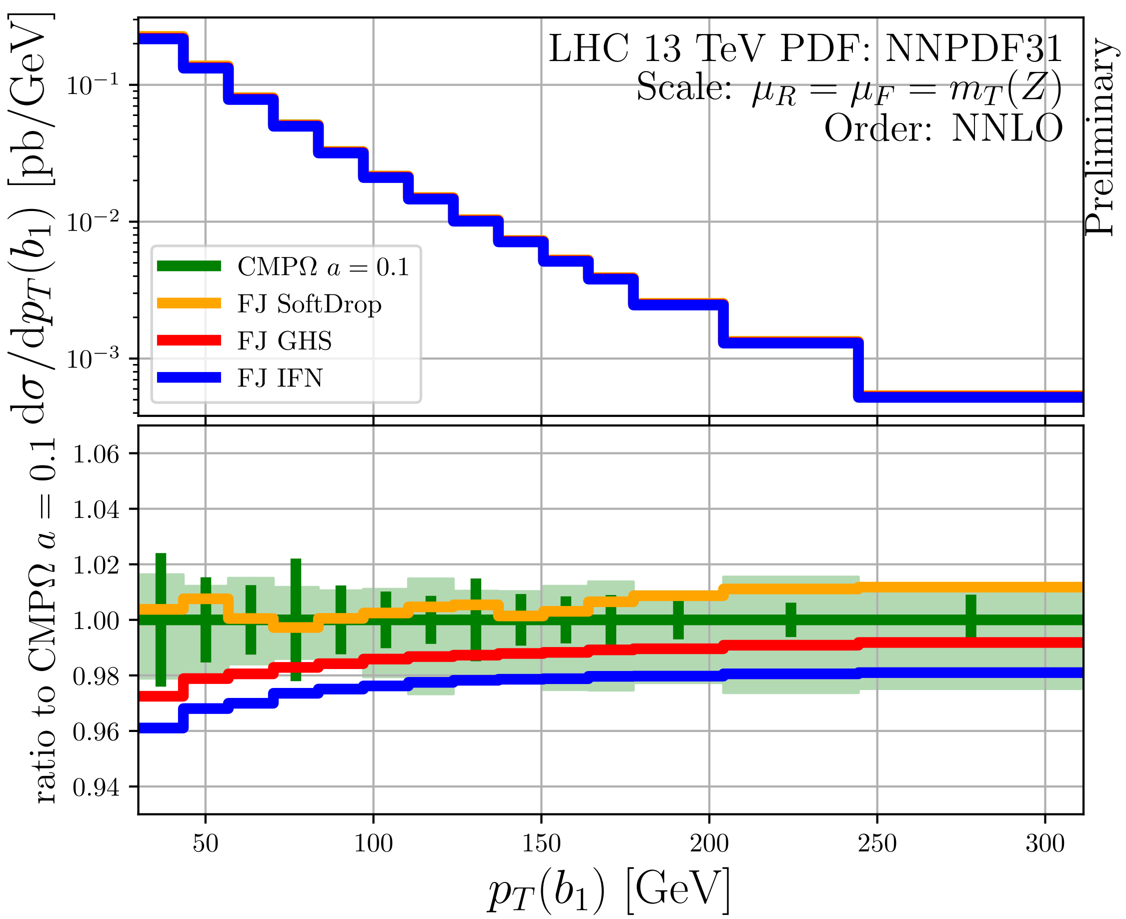
- Jade Soft Drop ($\beta > 0$) allows us to formulate a definition of flavour which is
  - viable from an experimental view point (original jets can be anti-k_t and the flavour algorithm is applied after jet clustering)
  - IRC safe through NNLO so that it can be used with state-of-the-art calculation
- however, the algorithm is unsafe at N^{3}LO: maybe one can think of applying recursive/iterative Soft Drop?



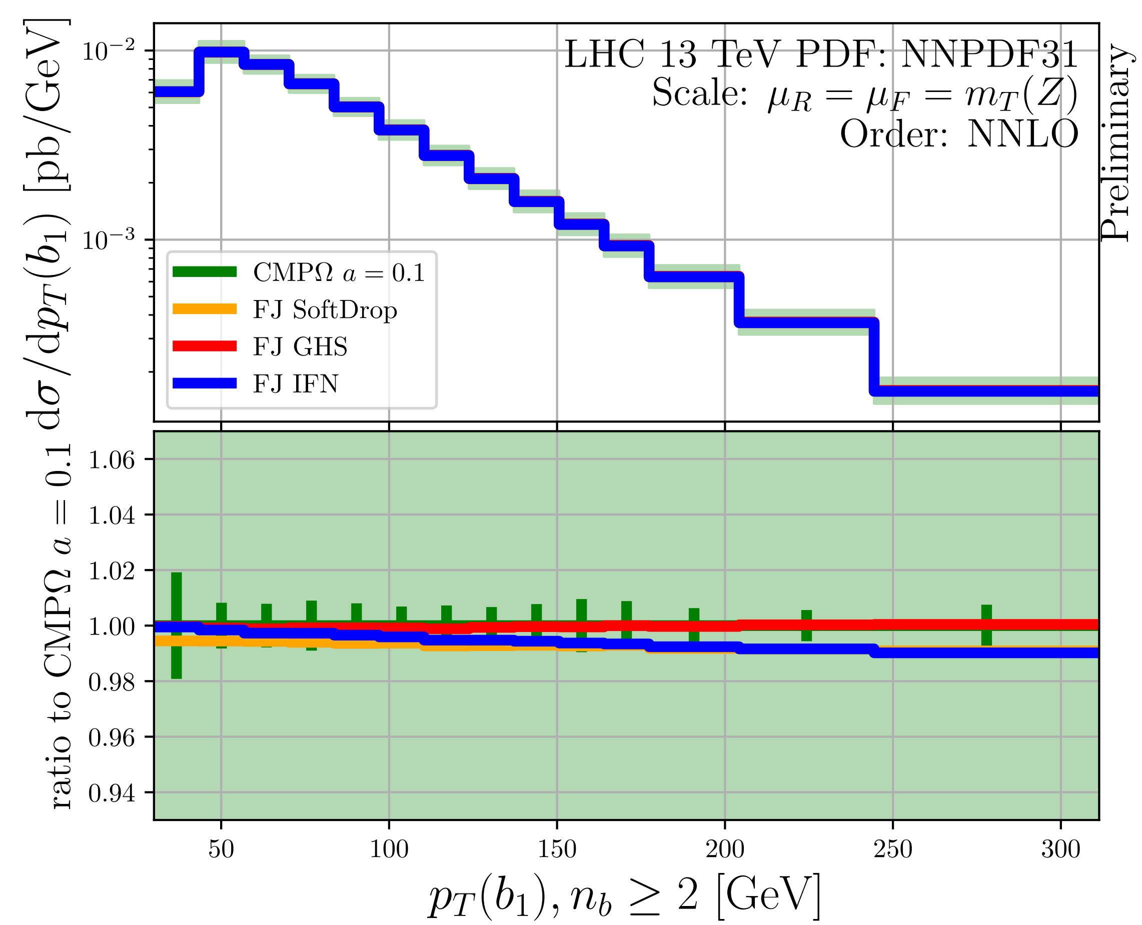
Les Houches 2023 study

- It is important to investigate IRC safety, resilience against non-perturbative effects and experimental viability of the 4 algorithms;
- a detailed study of these 4 algorithms was started at Les Houches 2023;
- regular biweekly meetings led to interesting studies;
- many results, here just a few ones to trigger discussion
- results are still preliminary!!!

Z+b jet @ NNLO (central rapidity)



- new algorithms agree at the percent level for most distributions

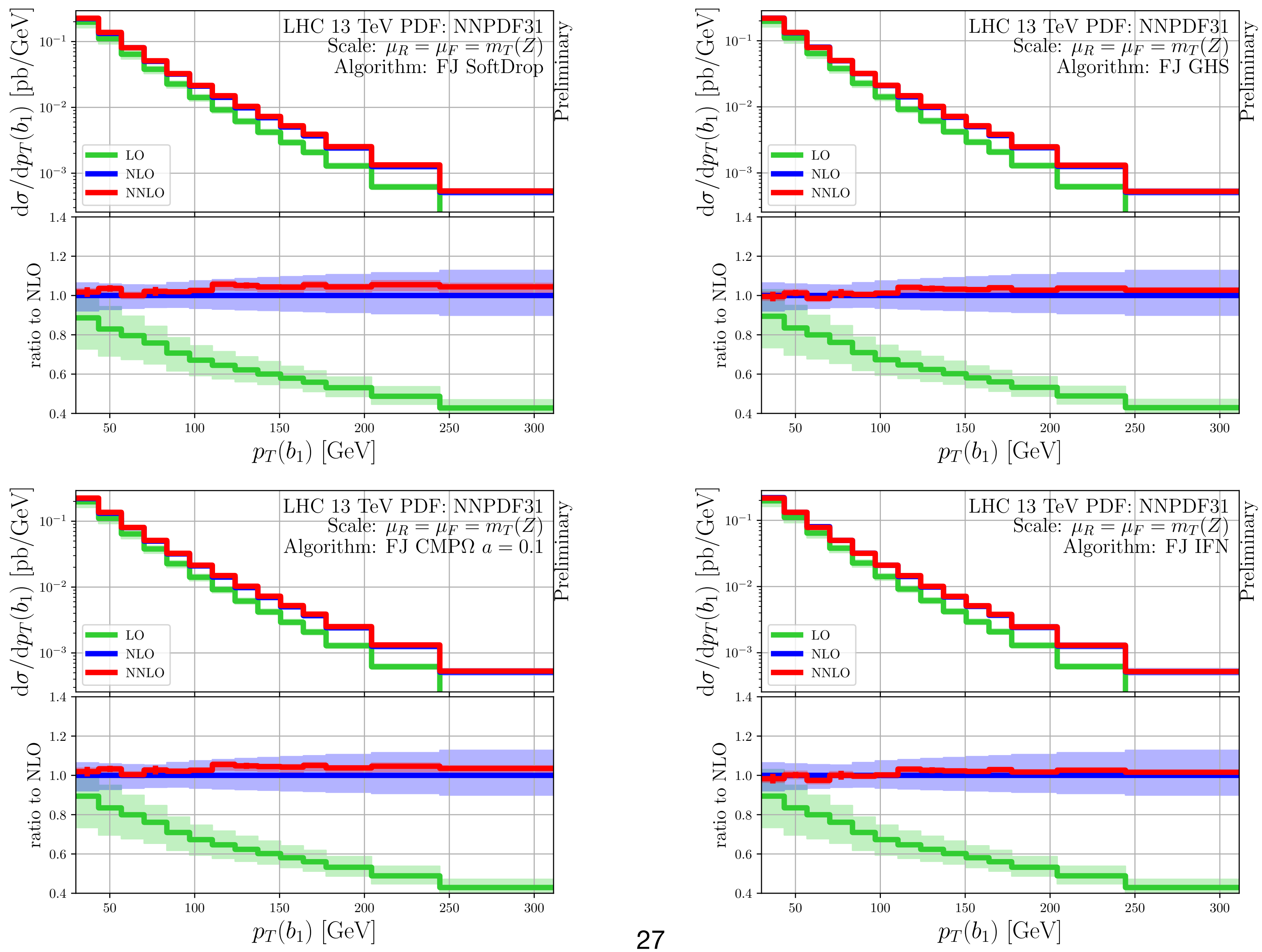


- more b-tags reduce the differences (less freedom for the algorithms)

plots by Rene Poncelet

Z+b jet @ NNLO (central rapidity)

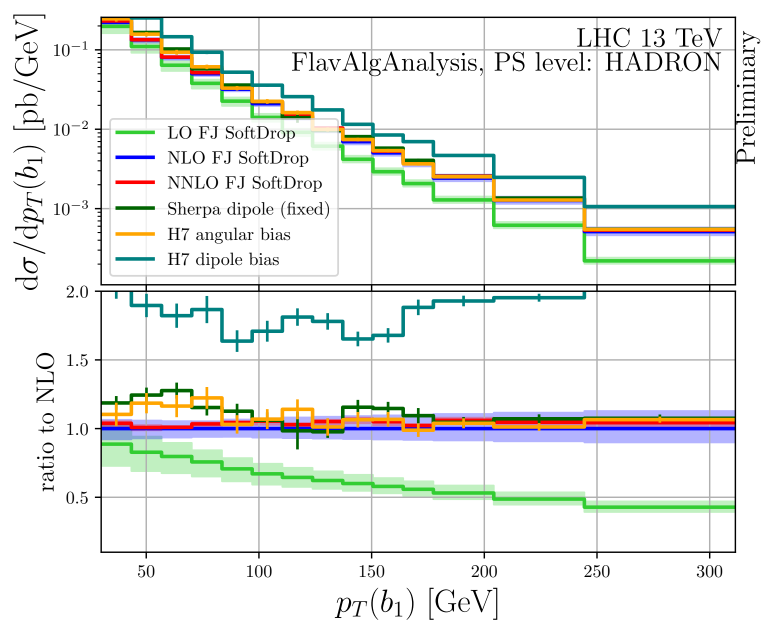
- perturbative convergence is good (remember that SDflavour not IRC safe beyond NNLO)

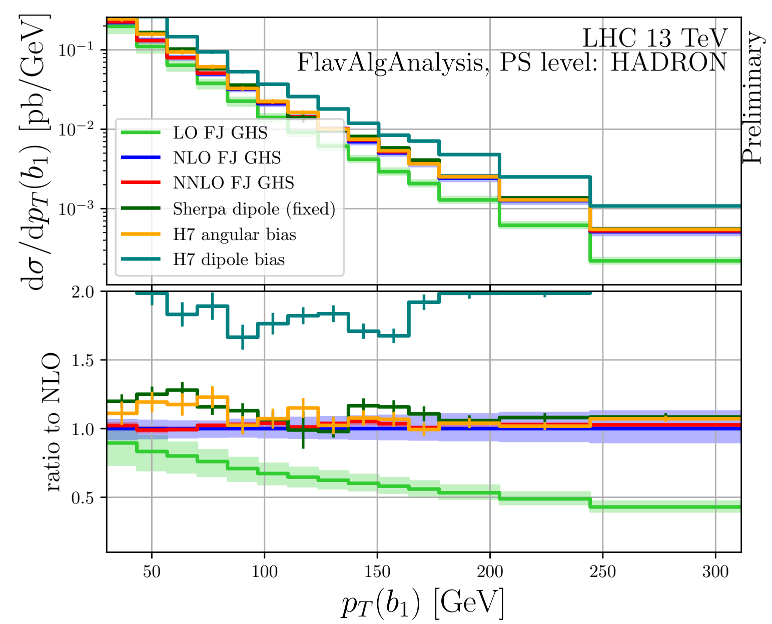


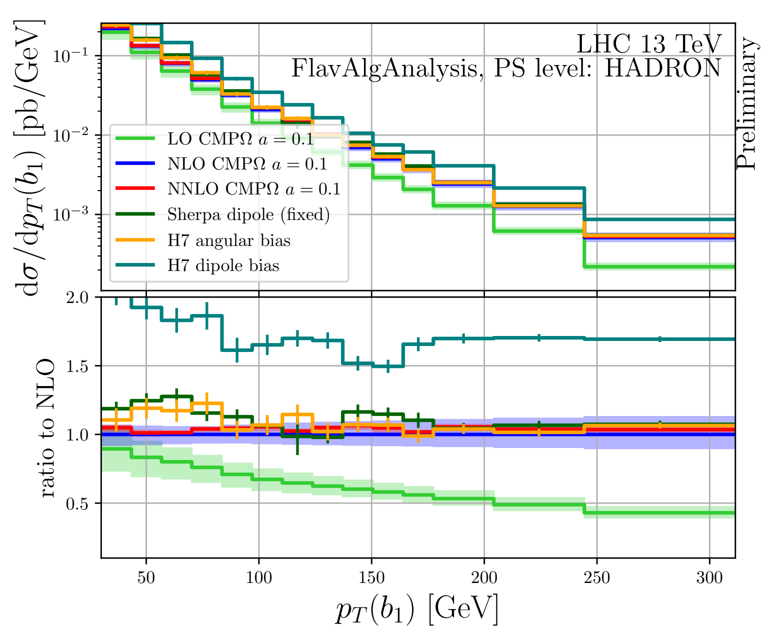
plots by Rene Poncelet

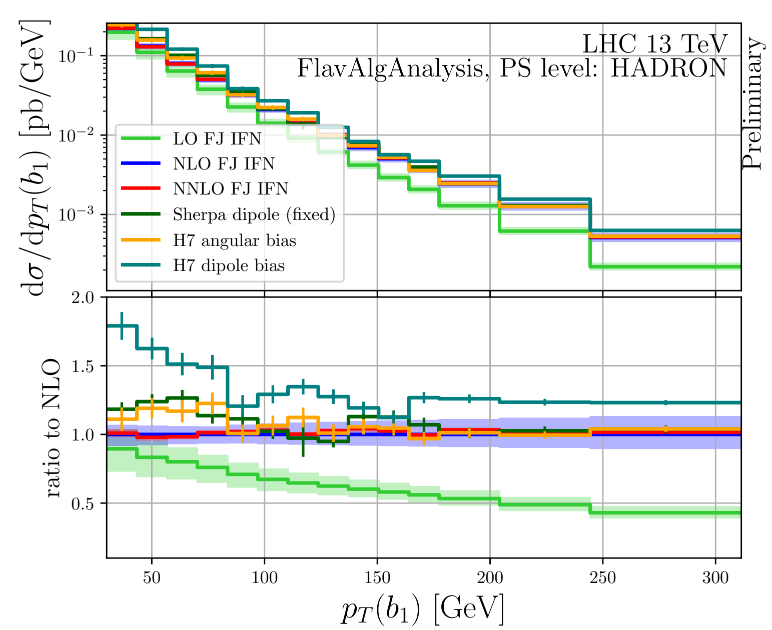
Z+b jet @ NLO+PS (central rapidity)

- some differences appear with the parton shower
- only IFN can handle massless quarks in the shower (H7 dipole)
- this leads to importante differences at high p_T and for c-jets









plots by Rene Poncelet and Daniel Reichelt

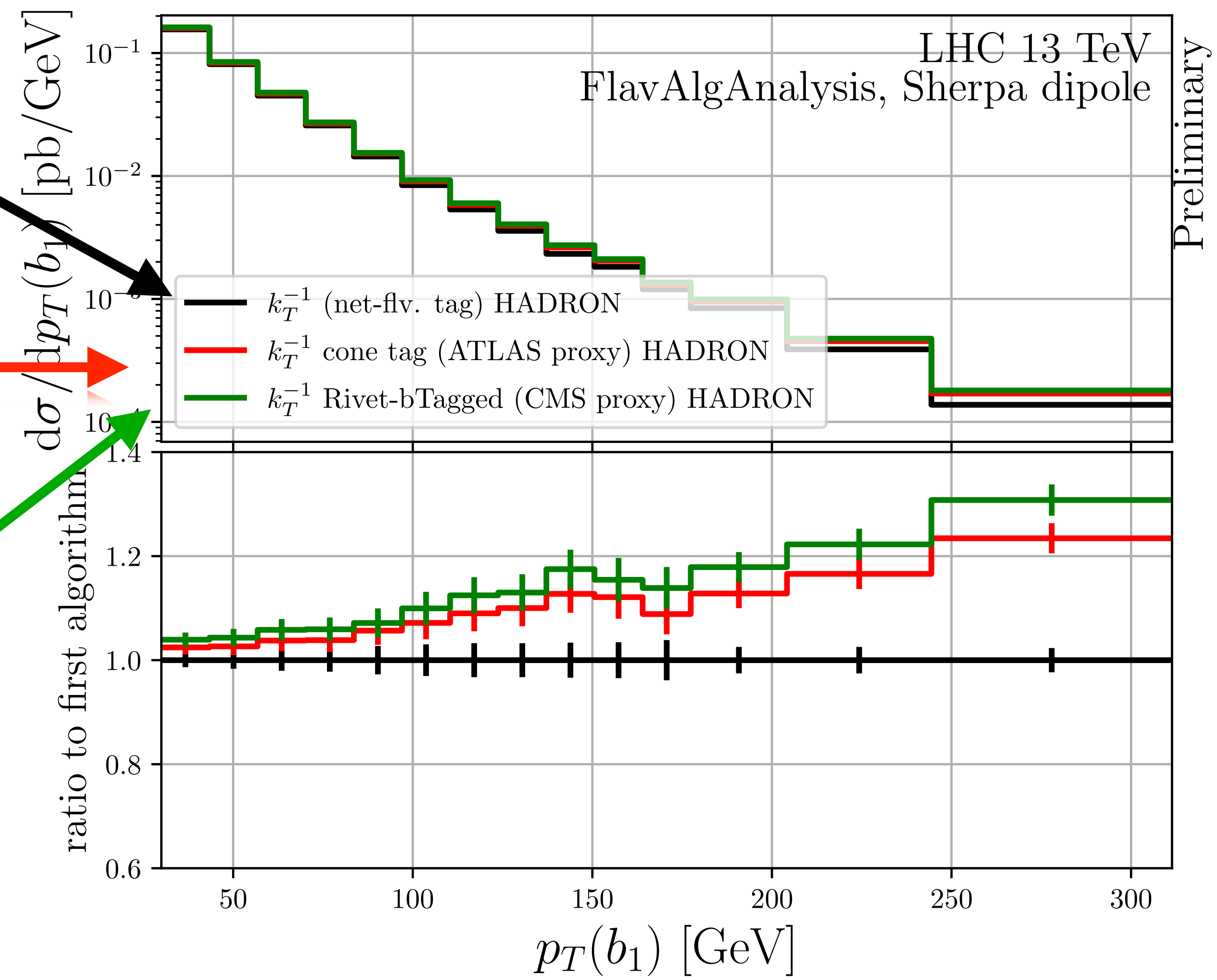
Comparison to experimental strategies

- NLO+PS with just anti-k_t jets but different strategies

anti-k_t with net flavour
(OK at NLO but not at NNLO)

cone with any flavour
(proxy to ATLAS)

Rivet b-tagging with any flavour
(proxy to CMS)



- large differences with current experimental strategies, likely due to net-flavours VS any-flavour

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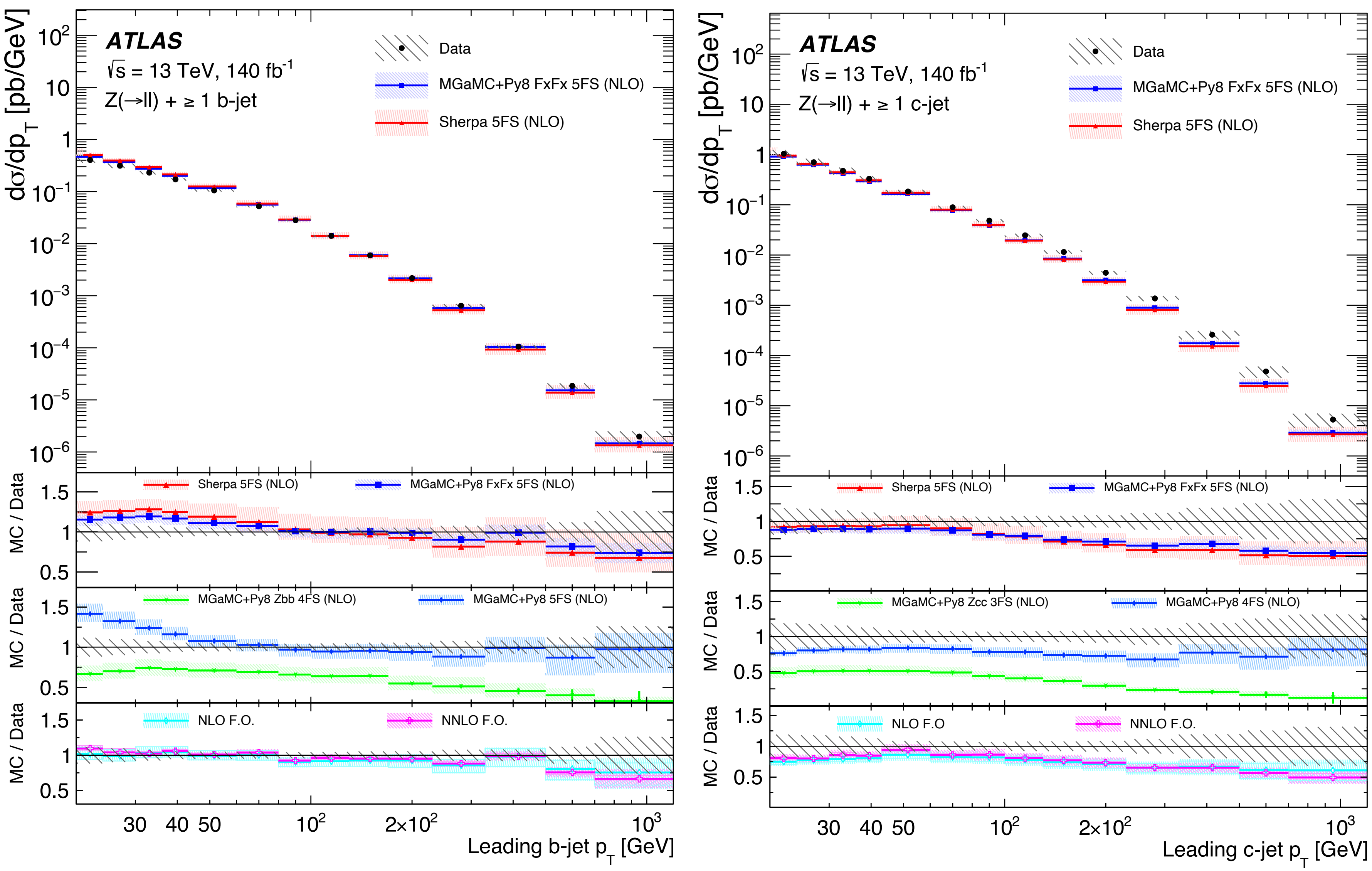
Does any of this matter?

- recent ATLAS measurements or Z+HF (b/c) jet
- important measurements for SM tests and PDFs



ATLAS (2024)

- at large p_T non-perturbative corrections are small and comparison to fixed-order makes sense
- however, unfolding to IRC safe algorithms can be sizeable (sometimes bigger than the NNLO correction)
- most of the effect is likely due to any-flavour vs net-flavour

It does!

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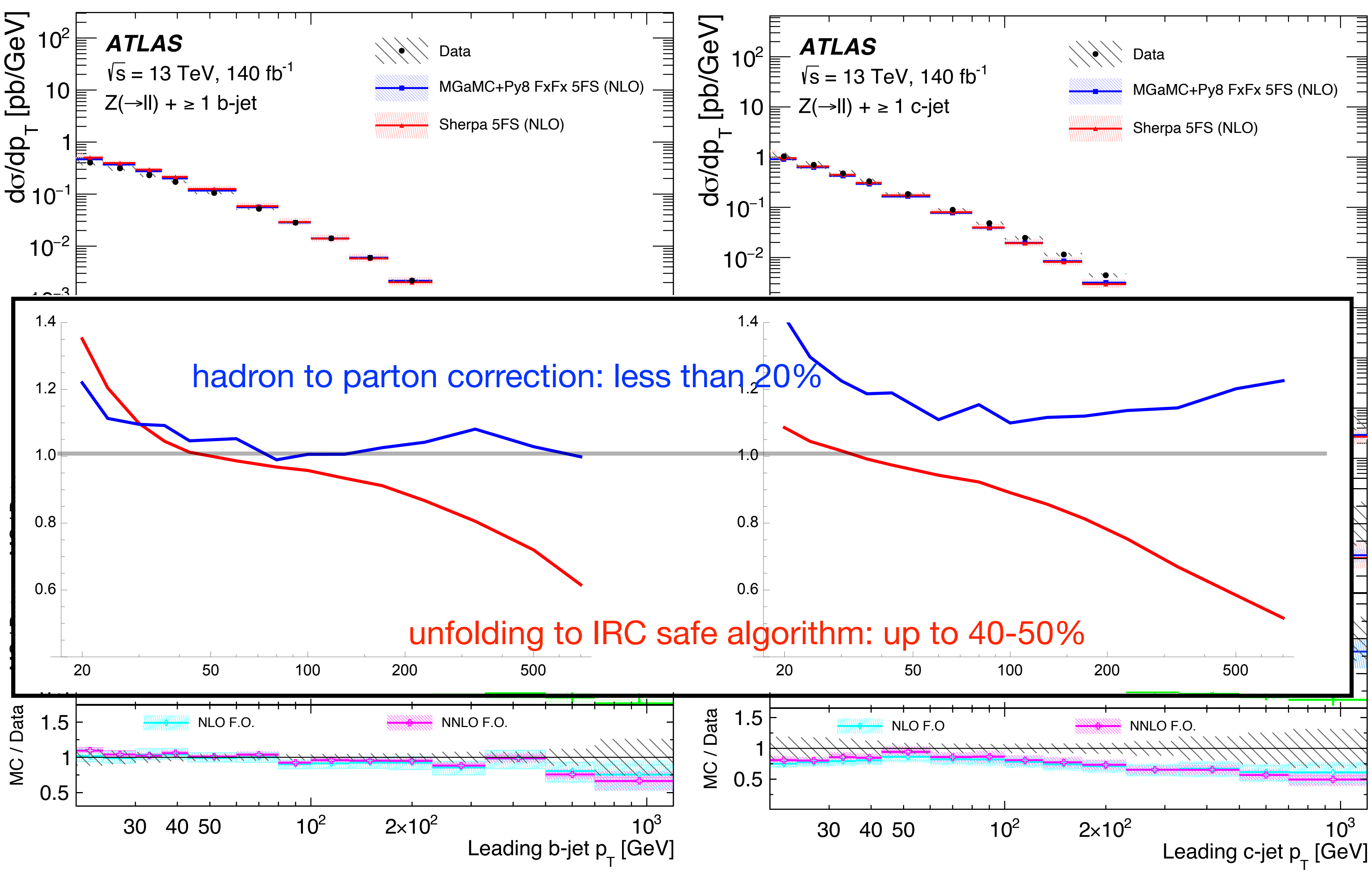

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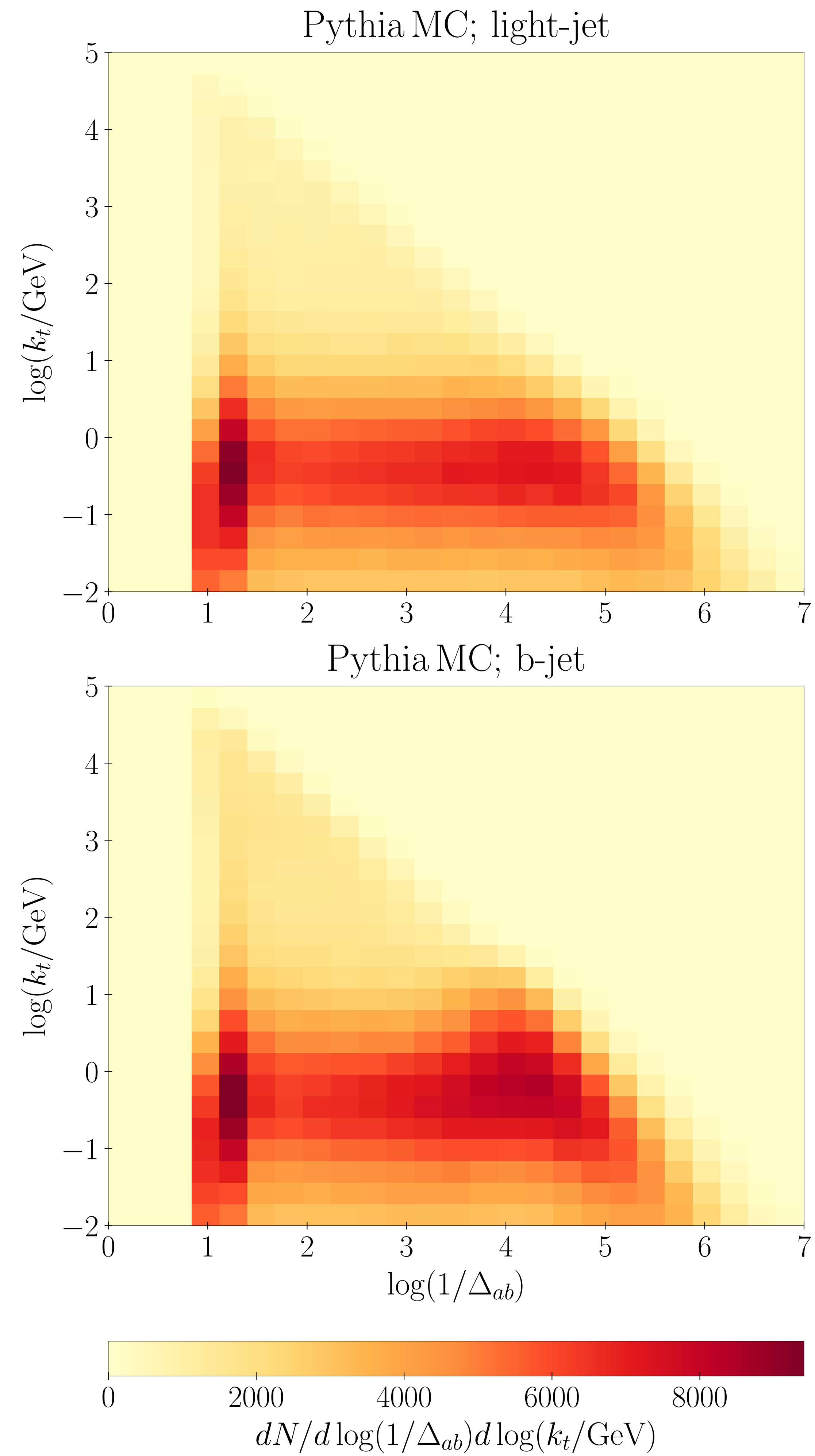
(apologies for the ugly correction-factor plots)

ATLAS (2024)

- **We must to better if we want to do NNLO phenomenology**

Heavy flavour jet substructure

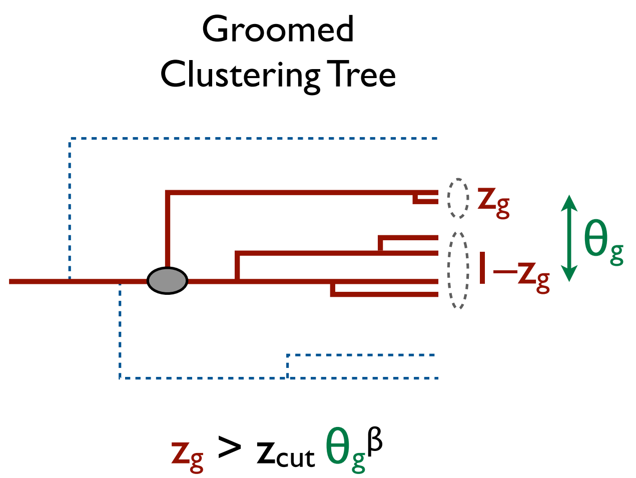
in collaboration with Simone Caletti, Prasanna Dhani, Oleh Fedkevych, Andrea Ghira, Gregory Soyez

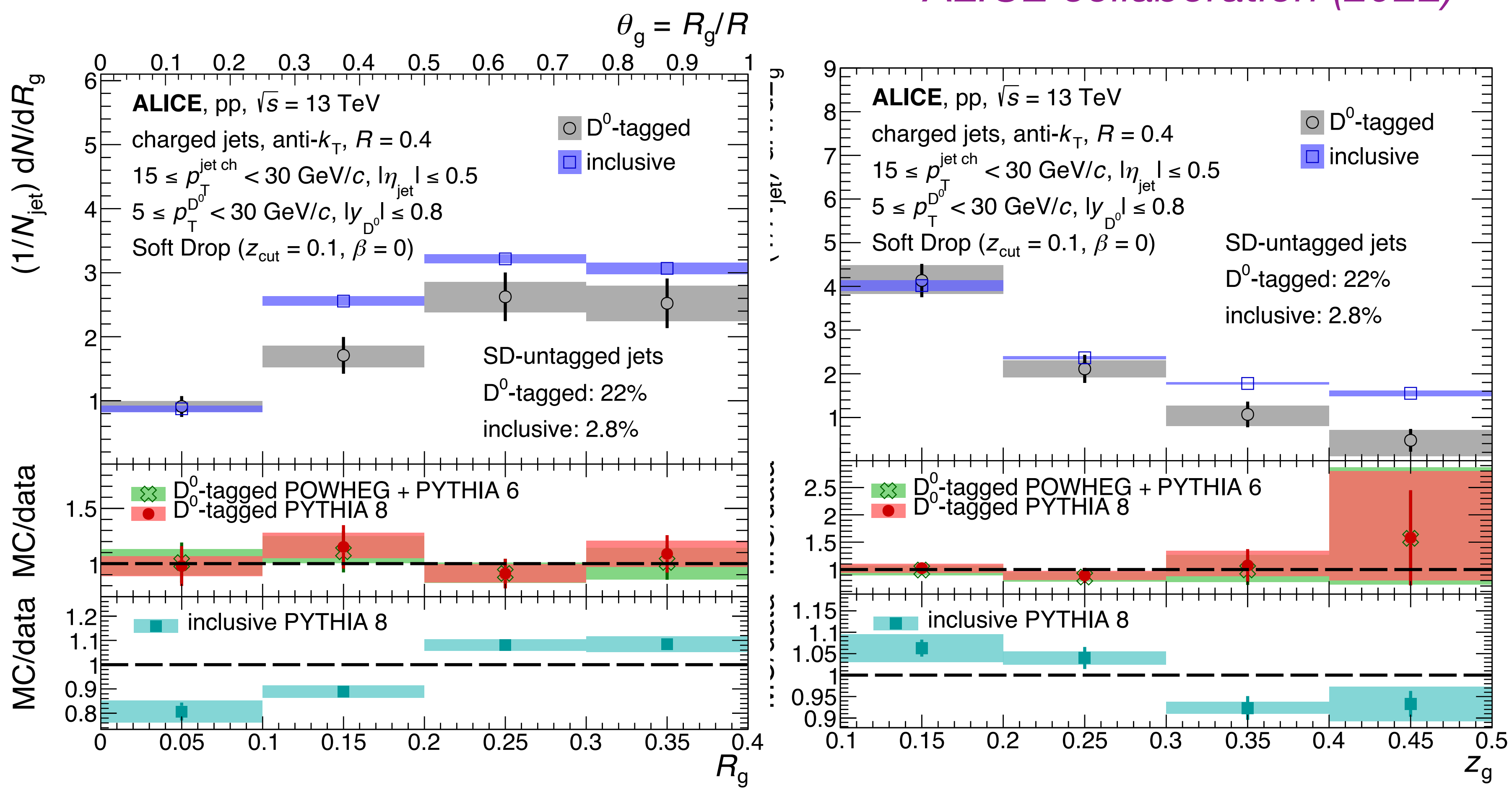


Jet substructure to expose the dead-cone

- jet substructure techniques are being exploited to measure the dead-cone effect at the LHC
- for instance Soft Drop is a very-well understood grooming techniques (high-precision calculation, many measurements)

ALICE collaboration (2022)



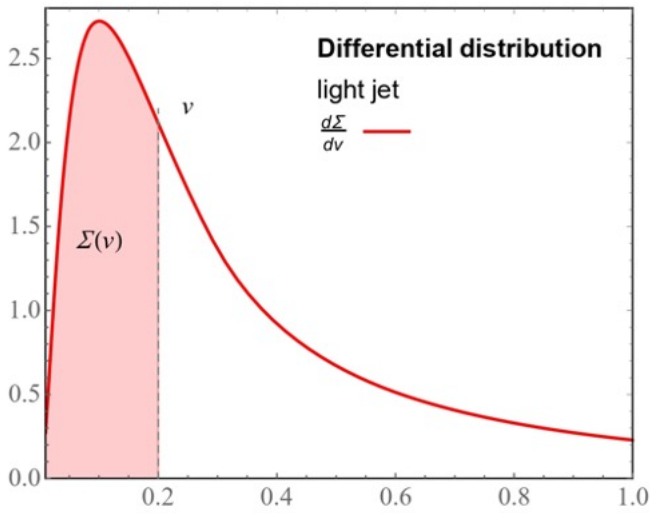


- How well do understand and model HF jet substructure?

All-orders calculations with HF

- heavy-flavour jets are characterised by a variety of scales
  - hard scale of the process *Q* (c.o.m energy, jet p_T, …)
  - heavy flavour mass *m* (much larger than Λ_{QCD})
  - scale *vQ* set by the HF property we want to measure (e.g. a substructure variable)
- (multiple) resummations become relevant and it is important to understand the hierarchy between the different scales
- we focus our attention on the (normalised) cumulative distribution

$$\Sigma(v) = \frac{1}{\sigma_0} \int_0^v \mathrm{d}v' \frac{\mathrm{d}\sigma}{\mathrm{d}v'}$$

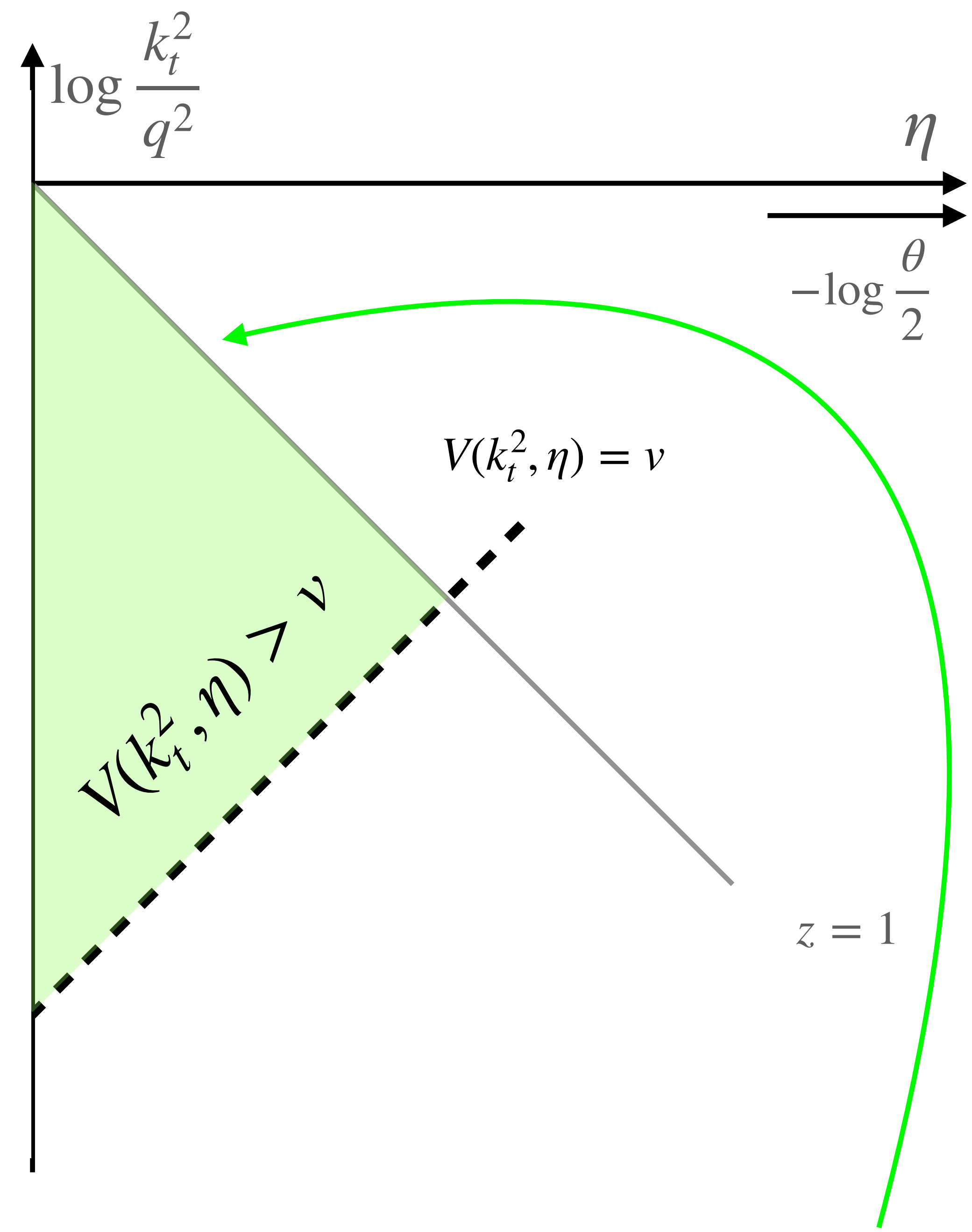


Lund plane - a short review

- Lund planes are a powerful way to visualise the kinematics of soft/collinear emissions
- IRC observables can in soft and collinear

$$V(k_t^2, \eta) = d \left(\frac{k_t^2}{q^2} \right)^a e^{-b\eta}$$

- coloured area represents the Sudakov form factor (i.e. the resummed exponent *R*)
- to NLL simple one-loop exponentiation receives corrections from multiple-emission and non-global logarithms



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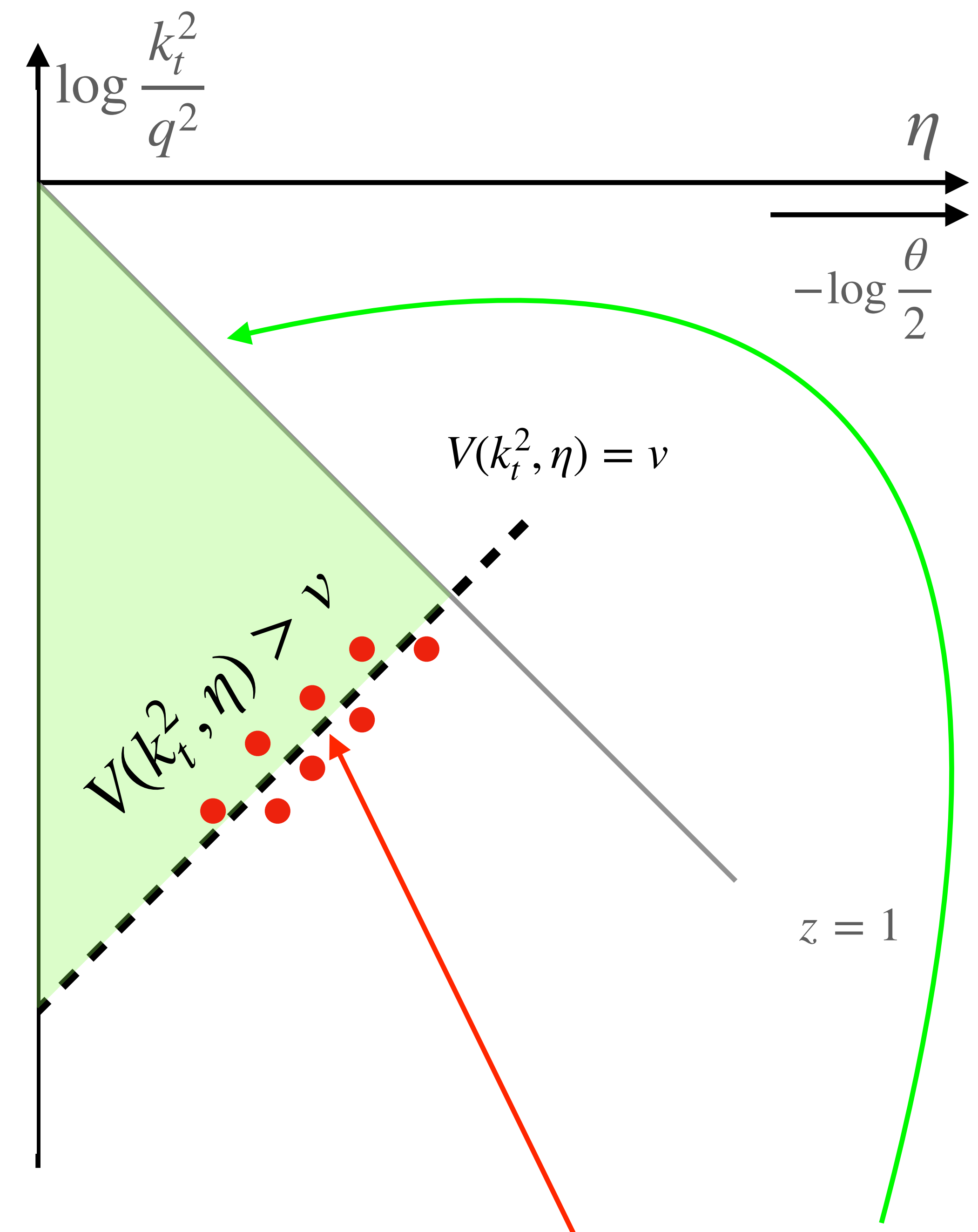

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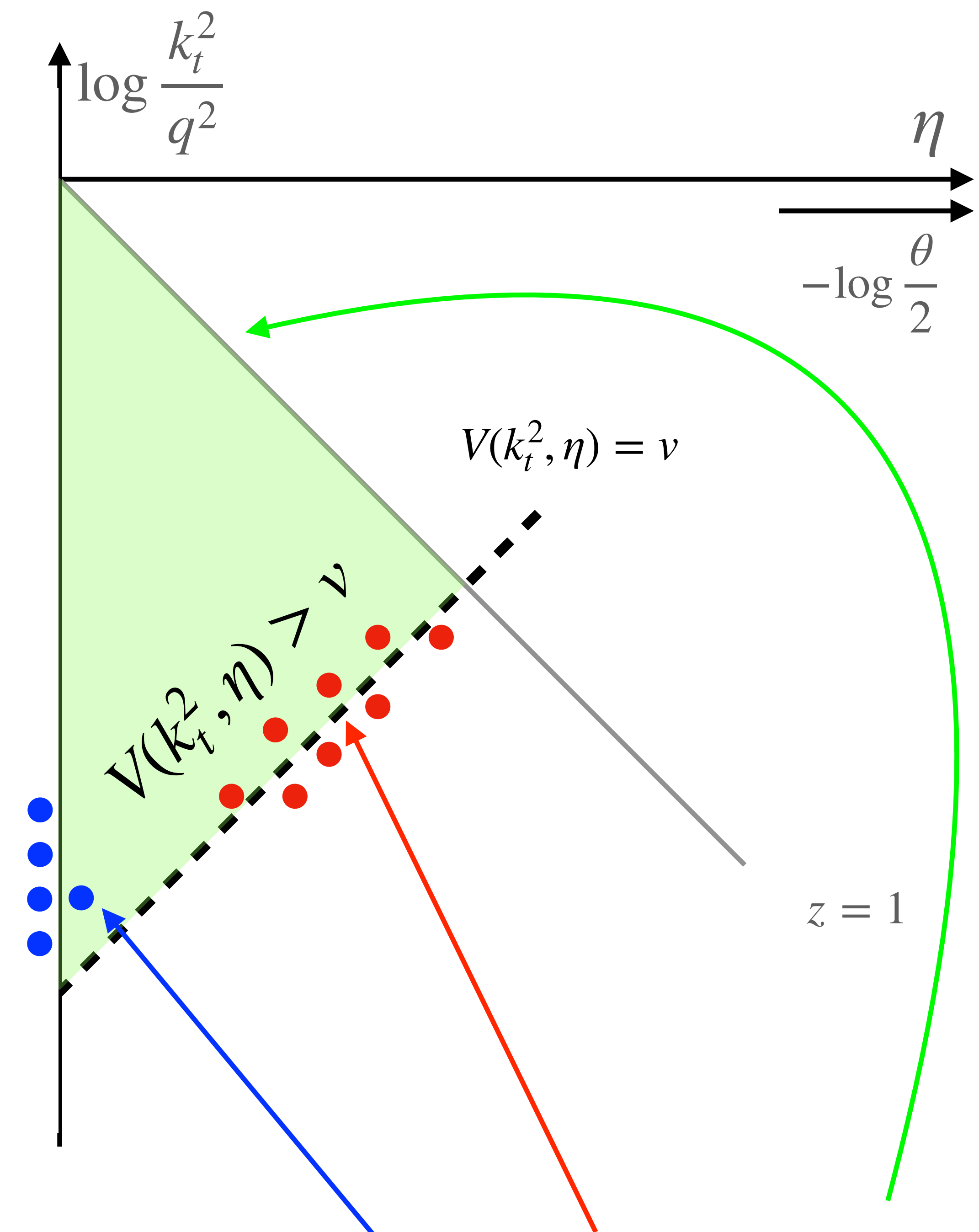

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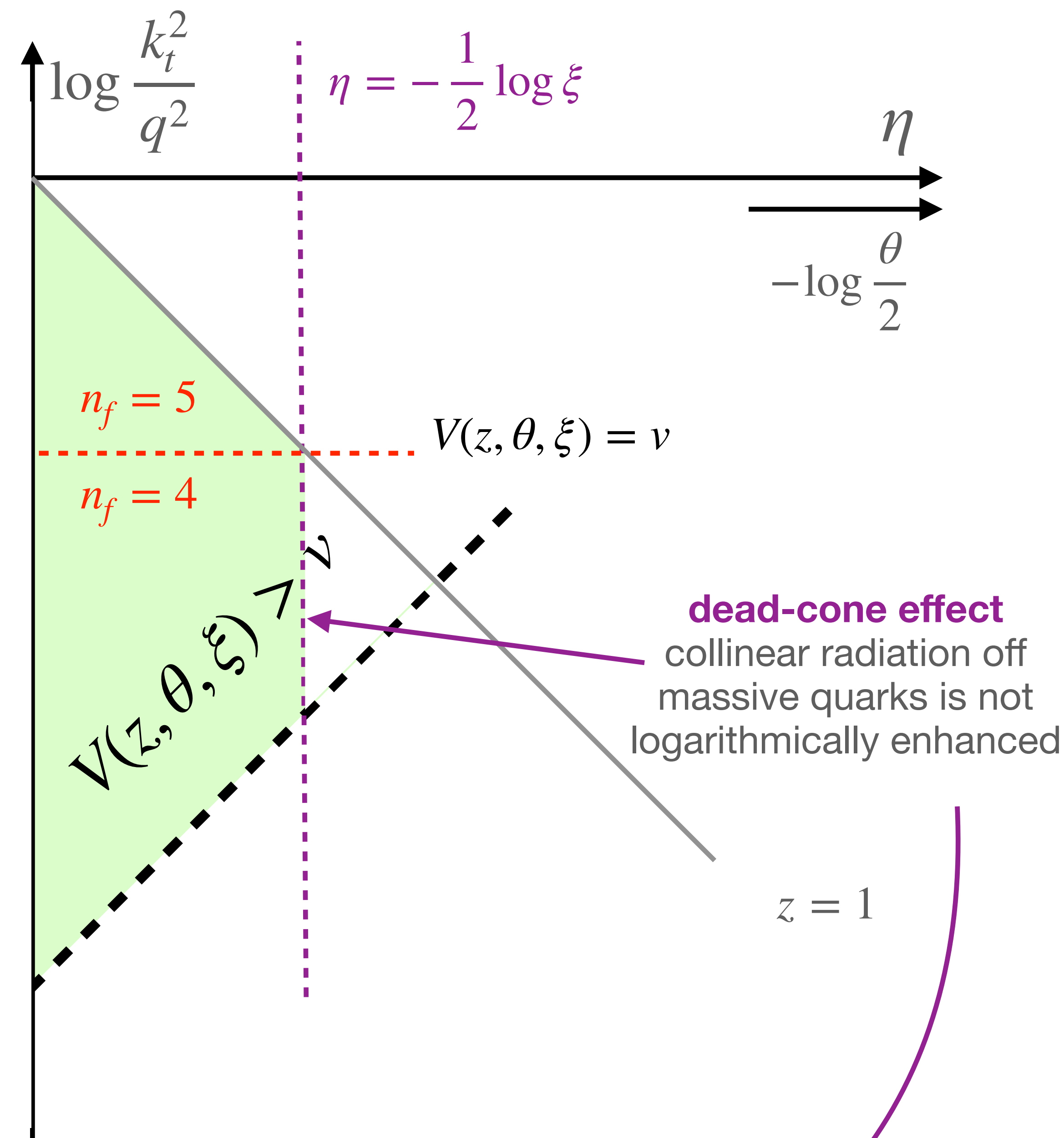
Lund plane with masses

- the presence of masses introduce new vertical (purple) boundary, the so-called dead-cone effect

- the collinear limit should be replace by the quasi-collinear one (angles and mass are small but of the same order)

- running coupling with variable flavour number: the horizontal (red) line marks the $n_f = 4, 5$ boundary

- the NLL (both v and ξ) radiator reads



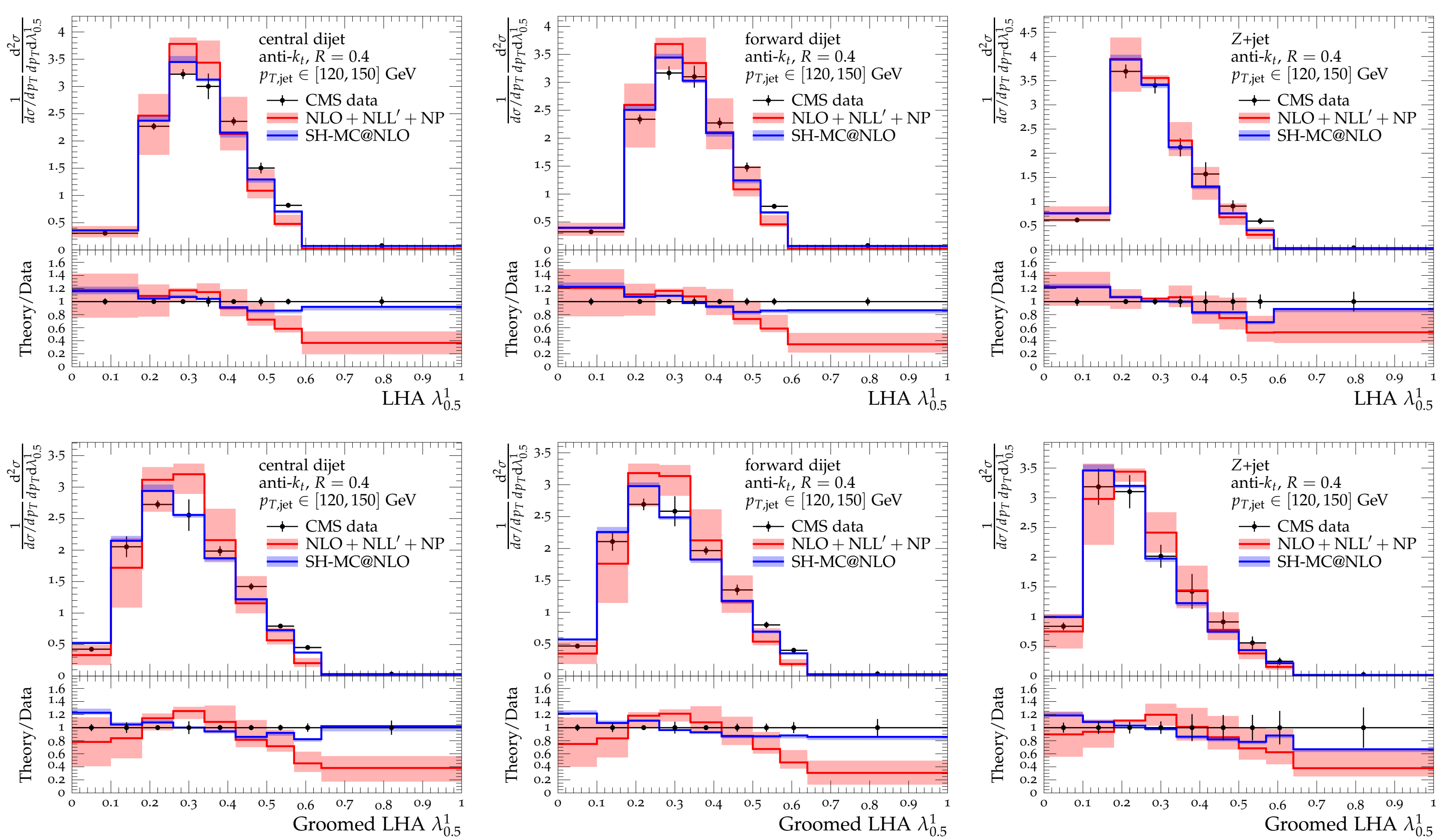
$$R(v) = \int_{z^2 m^2}^{Q^2} \frac{dk_t^2}{k_t^2} \int_0^1 dz P_{Qg} \frac{\alpha_s^{\mathrm{CMW}}(k_t^2)}{2\pi} \Theta(\mathcal{V}(k_t^2, \eta) - v)$$

Jet angularities (on light jets)

- jet angularities allow us to probe the internal QCD dynamics of jets

$$\lambda_\alpha = \sum_{i \in \text{jet}} \frac{p_{ti}}{p_t} \left(\frac{\Delta R_i}{R} \right)^\alpha$$

CMS collaboration (2021)



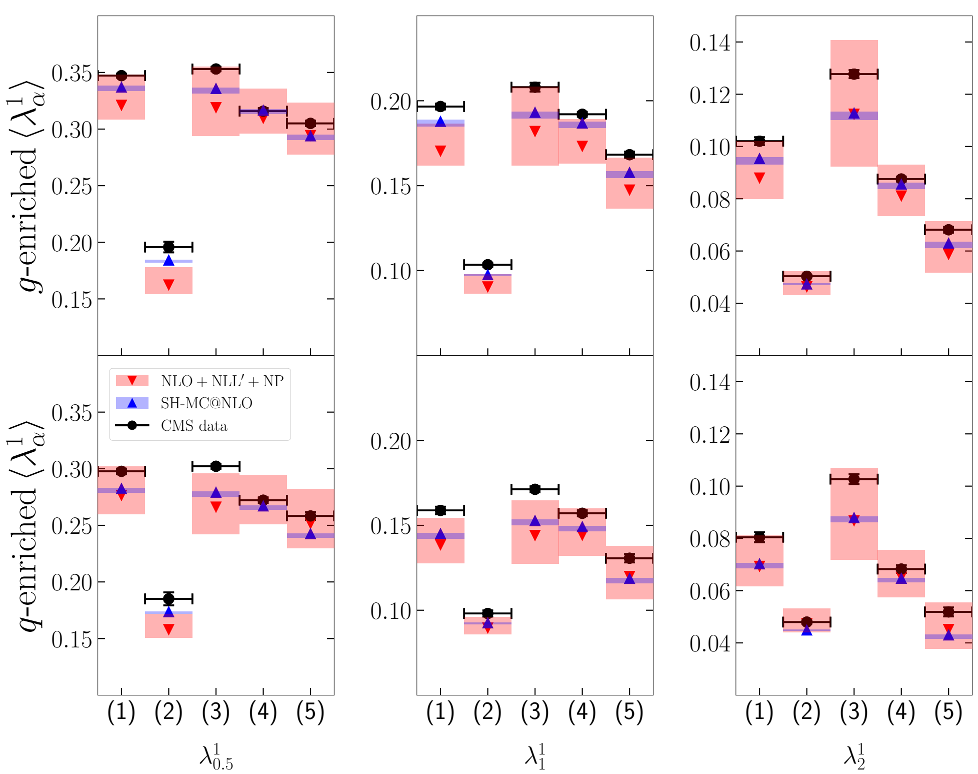
- a wealth of high-quality data combined with solid theory description
- a lot of interesting phenomenology!

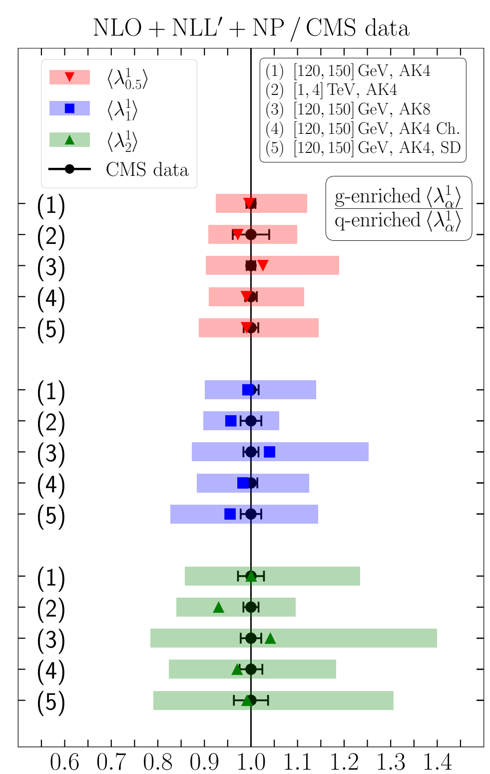
Reichelt, Caletti, Fedkevych, SM, Schumann, Soyez (2021)

Detailed pheno studies

- measurements of distributions Z+jet and dijets in different transverse momentum and rapidity bins allows us to probe samples with rather different quark/gluon components

configuration	type of jet	$p_{T,\text{jet}}$ [GeV]	g-enriched	q-enriched
(1)	ungroomed $R = 0.4$	[120,150]	dijet central	Z+jet
(2)	ungroomed $R = 0.4$	[1000,4000]	dijet central	dijet forward
(3)	ungroomed $R = 0.8$	[120,150]	dijet central	Z+jet
(4)	ungroomed $R = 0.4$ (tracks only)	[120,150]	dijet central	Z+jet
(5)	SoftDrop ($\beta = 0,\ z_{\text{cut}} = 0.1$) $R = 0.4$	[120,150]	dijet central	Z+jet





- mean values confirm standard picture: g's radiate more than q's
- our calculation tends to underestimate the mean values
- however, it does so democratically for q's and g's: no appreciable bias
- beware! NLO corrections can significantly alter q/g fractions

- Can we study HF jets at the same level of precision?

Jet angularities (on HF jets)

- what is a sensible definition of jet angularities for HF jets?
- standard definition vs dot-products: the devil's in the details!

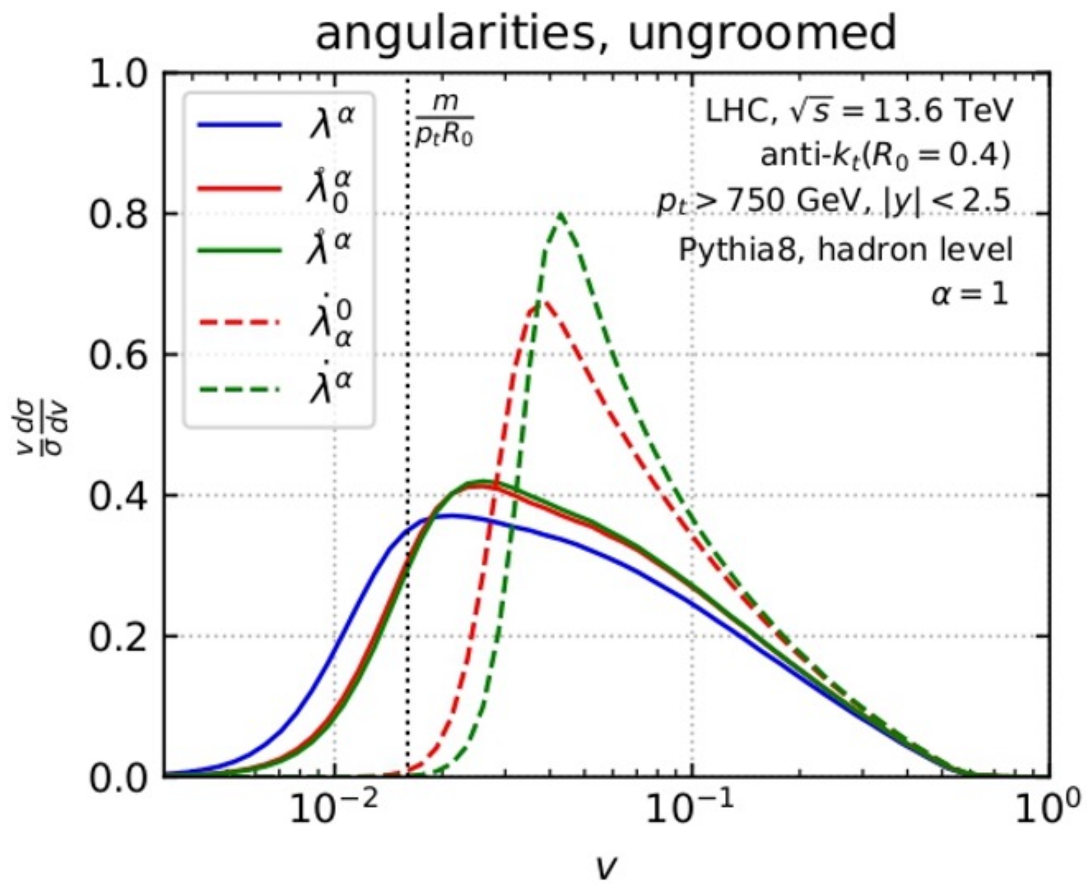
$$\lambda^\alpha = \sum_i \frac{p_{ti}}{p_t}\left(\frac{\Delta R_i}{R_0}\right)^\alpha \quad + \quad \begin{aligned} \dot{\lambda}_0^\alpha &= \sum_i \frac{p_{ti}}{p_t}\left(\frac{2p_i\cdot n_0}{p_{ti}R_0^2}\right)^{\frac{\alpha}{2}}, & \dot{\lambda}^\alpha &= \sum_i \frac{p_{ti}}{p_t}\left(\frac{2p_i\cdot n}{p_{ti}R_0^2}\right)^{\frac{\alpha}{2}}, \\ \mathring{\lambda}_0^\alpha &= \sum_{i\neq n} \frac{p_{ti}}{p_t}\left(\frac{2p_i\cdot n_0}{p_{ti}R_0^2}\right)^{\frac{\alpha}{2}}, & \mathring{\lambda}^\alpha &= \sum_{i\neq n} \frac{p_{ti}}{p_t}\left(\frac{2p_i\cdot n}{p_{ti}R_0^2}\right)^{\frac{\alpha}{2}}, \end{aligned}$$

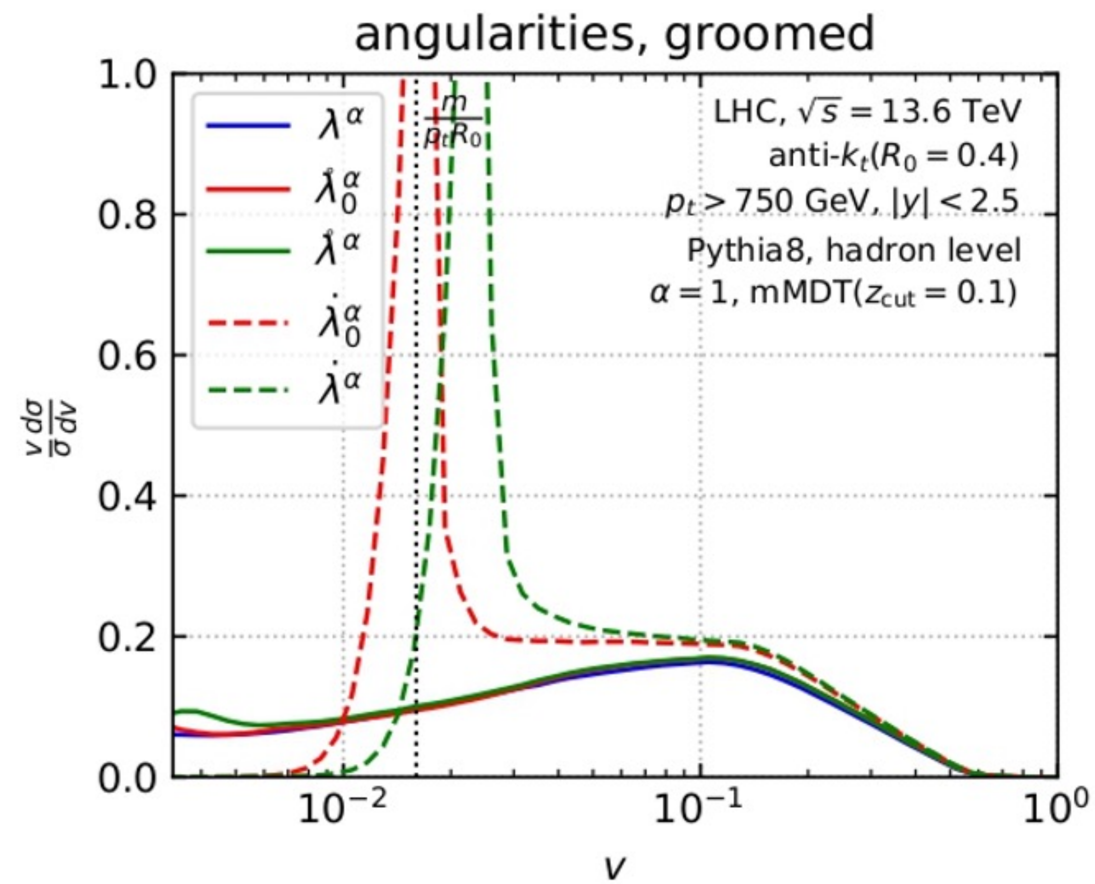
n (n_0) is (massless) 4-vector built with the WTA axis

- all definitions coincide in the collinear limit with massless partons (and axis)
- all definitions share the same NLL behaviour even with massive objects
- dot-product definitions can simplify calculations

Lee, Shrivastava, Vaidya (2019)

A first look at b-jets with MCs





- dotted-distributions exhibit peaks and kinematical end-points (behaviour magnified for groomed jets)
- their origin can be understood by looking at the quasi-collinear limits
- for groomed jets also circled-observables have

$$\lambda^\alpha = \sum_i \frac{p_{t_i}}{p_t}\left(\frac{\Delta R_i}{R_0}\right)^\alpha$$

$$\mathring{\lambda}^\alpha_0 \simeq \sum_{i \neq n} \frac{p_{t_i}}{p_t}\left(\frac{m_i^2}{p_{t_i}^2 R_0^2} + \frac{\Delta R_i^2}{R_0^2}\right)^{\frac{\alpha}{2}},$$

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Mass effects: kinematics vs dynamics

- dot-products induce *kinematic* mass dependence in the observables
- this effect is large and completely overshadows *dynamical* mass effects in the matrix elements
- dot-product observables exhibit strong sensitivity to the quark (hadron) mass: good for tagging (and perhaps mass measurements?)
- but they should be avoided if we want to study the dead cone!

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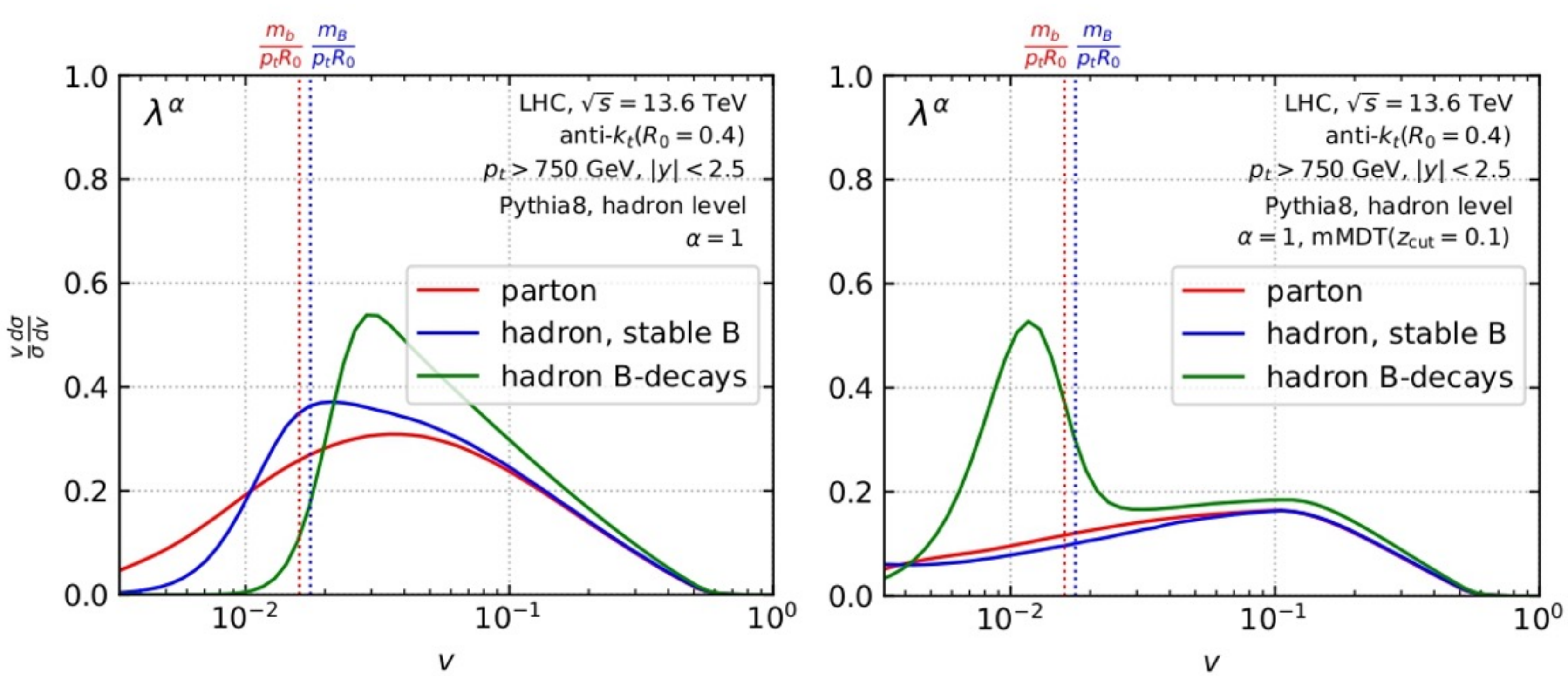
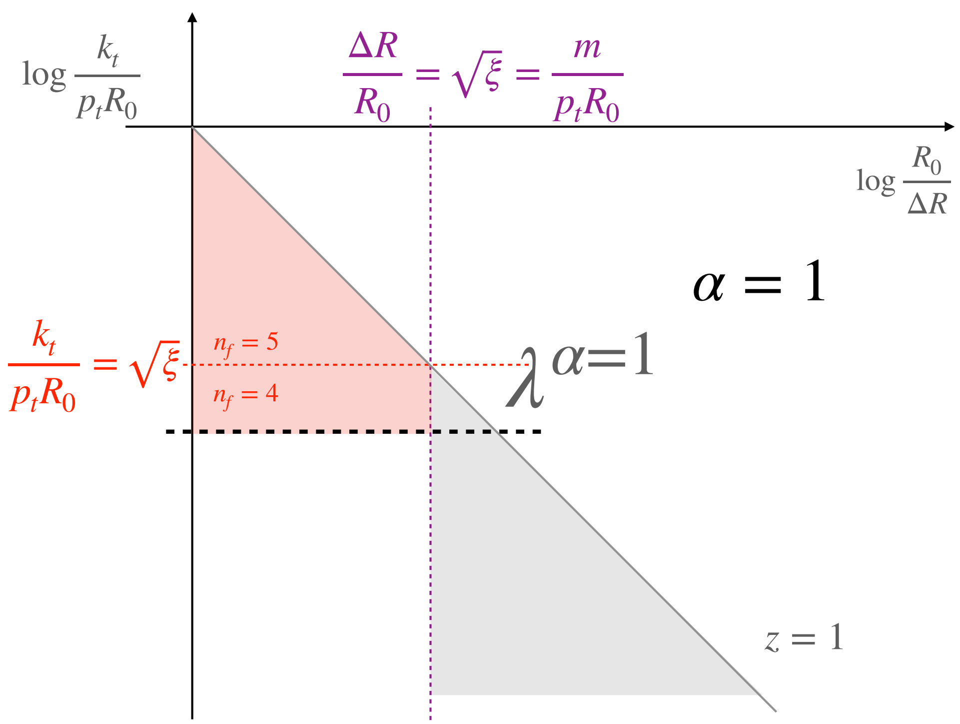
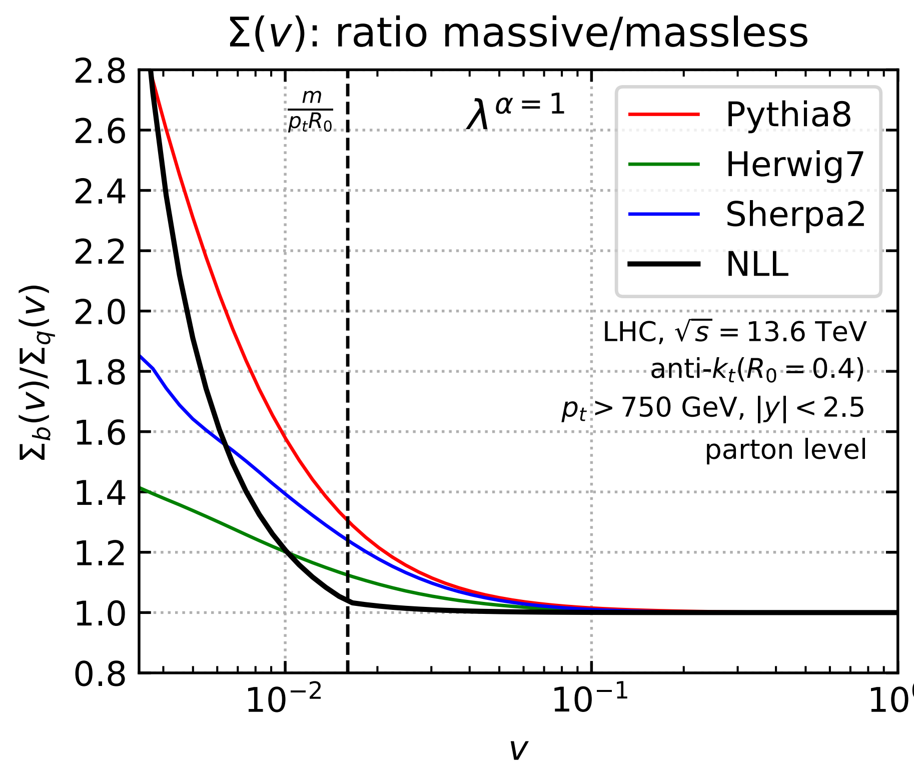
- but they should be avoided if we want to study the dead cone!
- Before computing resummed distributions: how big we expect non-perturbative corrections to be?

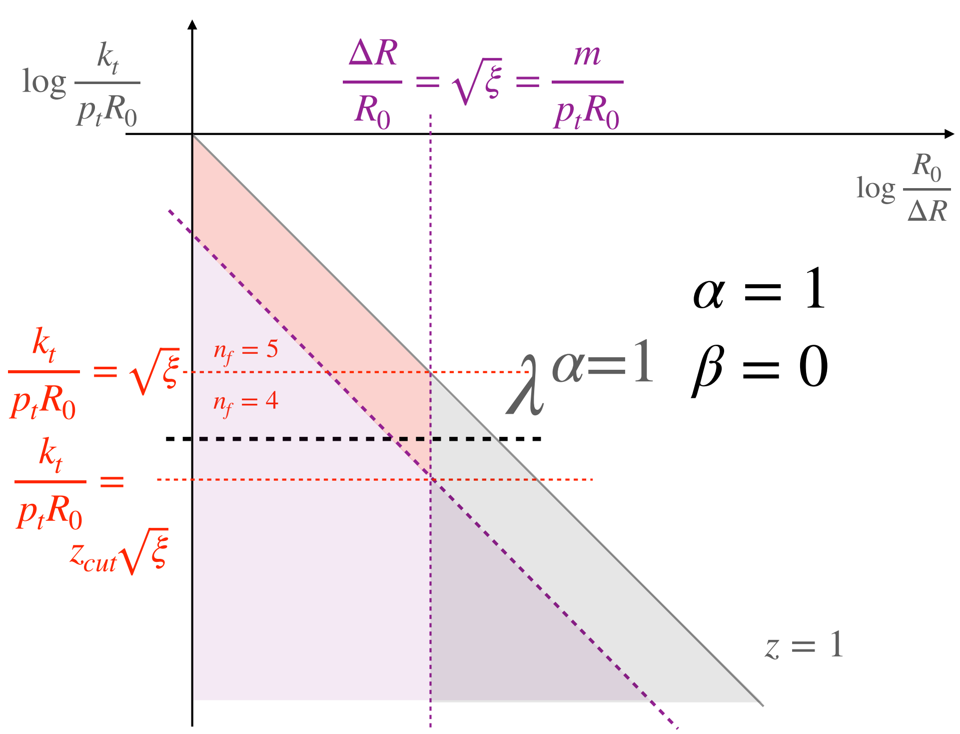


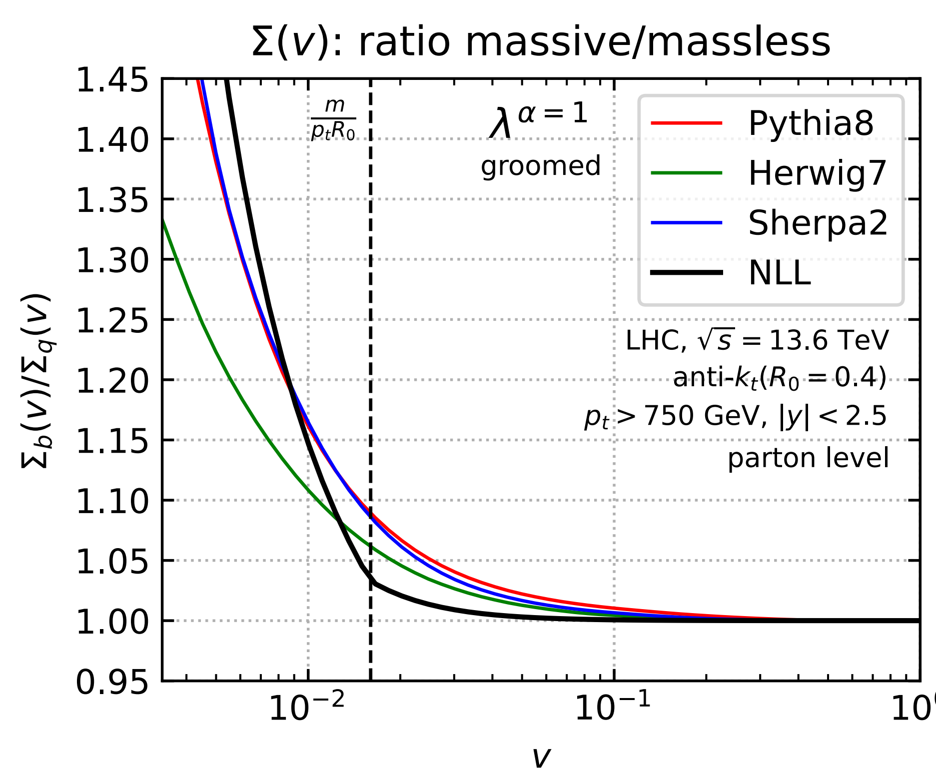
- groomed distributions seem robust provided we reconstruct the decay of the B hadron!
- on-going studies for experimental feasibility (e.g. *CMS talk at BOOST 2024*)

Resummation vs MC for λ^{α}



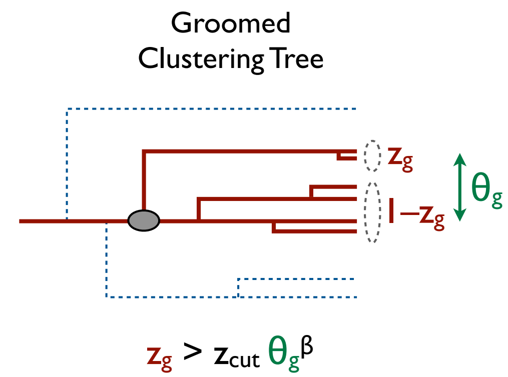


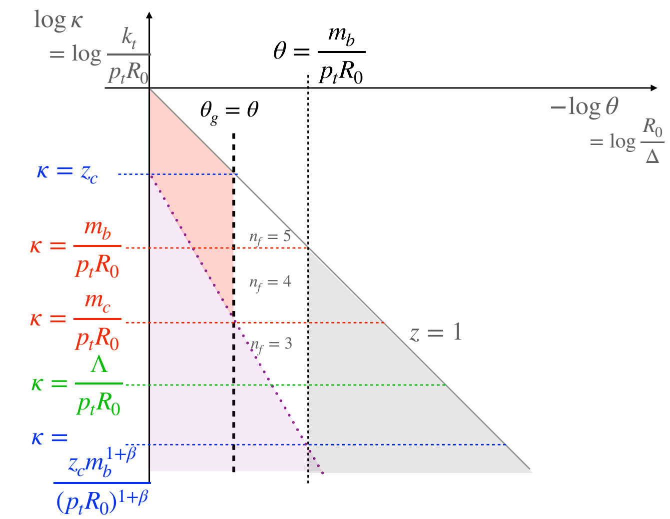


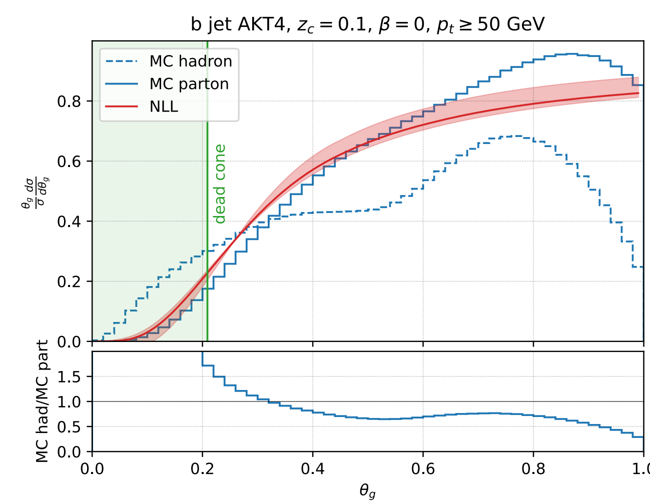


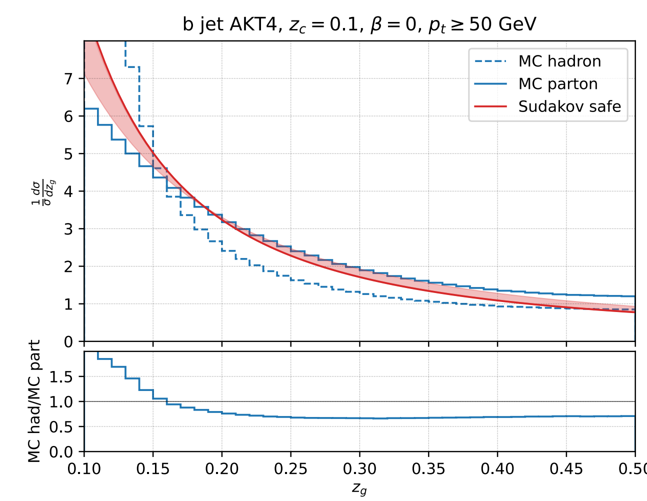
Towards HF jet phenomenology

- NLL resummation formalism for b/c jets worked out:
  - angularities
  - energy correlation functions
  - Soft Drop variables θ_g, z_g
  - work in progress on the Lund plane density









- What's left to do?
  - implementation in the SHERPA resummation plugin order to do deal with actual process and fiducial cuts
  - NLO matching
  - hadronisation corrections (transfer matrix approach)

Conclusions and Outlook

- Q1: How can we define flavoured jets in a sensible way?
  - New flavoured jet algorithms have been devised;
  - they are IRC safe either at NNLO or to all orders;
  - their behaviour in realistic experimental settings is currently under scrutiny (Les Houches study and internal work by the experiments);
- Q2: How well do we understand QCD final states with heavy-flavours?
  - We have performed a thorough study of kinematic and dynamic mass effects on jet substructure observables;
  - we have developed a formalism to perform resummation for HF jets (NLL for both mass and observable logs);
  - we have started its implementation in the SHERPA resummation plugin to perform actual phenomenology.

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THANKS FOR YOUR ATTENTION